NASA-CR-65099

Beckman®

FINAL REPORT

ELECTROENCEPHALOGRAPH SIGNAL CONDITIONERS

Contract NAS 9-3456

FACILITY FORM 602

N65-31185 (ACCESSION NUMBER)	(THRU)
68 (PAGES)	1 (CODE)
CR-65099 (NASA CR OR TMX OR AD NUMBER)	05 (CATEGORY)

NASA-MSC

Houston, Texas

GPO PRICE $ ______

CFSTI PRICE(S) $ 3.00

Hard copy (HC) ______

Microfiche (MF) $0.75

ff 653 July 65

April 23, 1965

Beckman® INSTRUMENTS INC

SCIENTIFIC AND PROCESS INSTRUMENTS DIVISION

FULLERTON, CALIFORNIA

FINAL REPORT

ELECTROENCEPHALOGRAPH SIGNAL CONDITIONERS

INTRODUCTION

This report is presented in four sections. The first section is a general description of Electroencephalography; the second section covers the development phase of the program; the third section describes the fabrication of the qualification and flight units; and the fourth section covers the qualification testing.

The contract design objectives are discussed, with the approach taken to meet these objectives. The problems encountered are discussed in detail along with the solutions found necessary to solve these problems.

1.0 ELECTROENCEPHALOGRAPHY

1.1 General

Electroencephalography refers to the measurement of the electrical activity of the brain, which is normally detected by placing electrodes on the surface of the head, thereby monitoring the electric potentials generated by the neurons of the brain. The output signal from electrodes placed on the surface of the scalp requires very high amplification since the potential difference between the electrodes is normally less than 100 microvolts, and may be as low as 30 microvolts.

The rhythmically varying potentials of the brain are normally recorded on oscillographs producing a permanent record called an electroencephalogram. The signal conditioning equipment should faithfully reproduce these signals with low distortion and without amplifying unwanted signals such as muscle responses. In general, the wave forms produced by the EEG system are non-periodic, low frequency, complex waves of extremely low power. These waves contain many frequencies with shifting phase relationships and varying amplitudes within the range of .2 to 100 cycles per second. Brainwaves have three predominant rhythms, namely alpha, beta, and gamma. The most common is the alpha rhythms which has a frequency range of approximately 8 to 13 oscillations per second. The alpha rhythm is desensitized or reduced in amplitude by visual activity and alert attention and for this reason it is often referred to as the resting rhythm. It is obtained most easily from the parietal and occipital lobes, although it can be detected almost anywhere on the scalp. The beta type of rhythm is dominated by waves of approximately 18 to 60 oscillations per second and is most easily detected in the frontal lobe. The gamma rhythms are those below 8 cps.

Although the electroencephalograms of different persons differ widely, the EEG of an individual, normal adult varies little from hour-to-hour or over periods of several months. Electroencephalographic records indicate many things about the subject, such as his state of alertness, and whether or not his eyes are open. The presence of the dominant rhythm and the frequencies and amplitudes of the brainwaves may be used to determine the subject's state of alertness. In addition, hypoxia tends to shift the rhythm toward the very low frequency and, therefore, indications are obtained on certain functions of the respiratory and circulatory systems, as well as the behavioral system. For this reason the occasional monitoring of EEG signals of an astronaut under conditions of stress or prolonged space travel is of interest. Furthermore, since the EEG signals of each individual astronaut can be monitored for many months prior to flight, any changes in these signals under conditions of space flight become more meaningful.

1.2 Problem Areas

Artifacts make the interpretation of electroencephalograms difficult. The muscles of the scalp, neck and jaws are stimulated continuously, causing electromyographic potentials to appear in the electroencephalograms. Electromyographic potentials may be eliminated primarily by providing a high common mode rejection ratio at the amplifier input, and to a large extent by filtering out frequencies higher than approximately 100 cps. Muscle potentials are recognizable by their spiky appearance, relatively high frequency and short duration. The magnitude of the electromyograph potentials vary considerably, but typically range from 1 to 3 mv for cardiac muscles and anywhere from 50 microvolts to 10 millivolts for skeletal muscles. The location of the EEG electrodes, if properly placed, tend to minimize the EMG interference, but nevertheless, since the EMG potentials are of greater magnitude, these interfering signals must be taken into consideration.

1.3 Characteristics of an Ideal Electroencephalograph

An ideal electroencephalograph should have the following characteristics:

o Input Impedance:	Infinite
o Input Coupling:	Direct Coupled-Zero Leakage Current
o Common Mode Rejection Ratio:	Infinite
o Noise Level:	Zero
o Frequency Response:	0.2 to 100 cps
o Harmonic Distortion:	Zero
o Output:	Stable
o Output Impedance:	Zero

In addition, when the electroencephalograph is intended for use in space, it should also have the following characteristics:

- Low Weight
- Small Physical Size
- Low Power Consumption
- Ability to Operate in Severe Environments

The desirability of having an infinite input impedance is often overlooked, but is a consequence of deterioration of the electrode-scalp interface with time, coupled with the necessity of rejecting high level common mode signals developed in or on the subject. (This is unrelated to the loading effect caused by low input impedance values.) Examination of Figure 1-1, which is a highly simplified equivalent circuit of the biological signal source, common mode signal generator, electrode interface, and the signal conditioner input, will aid in understanding the mechanism whereby this is so.

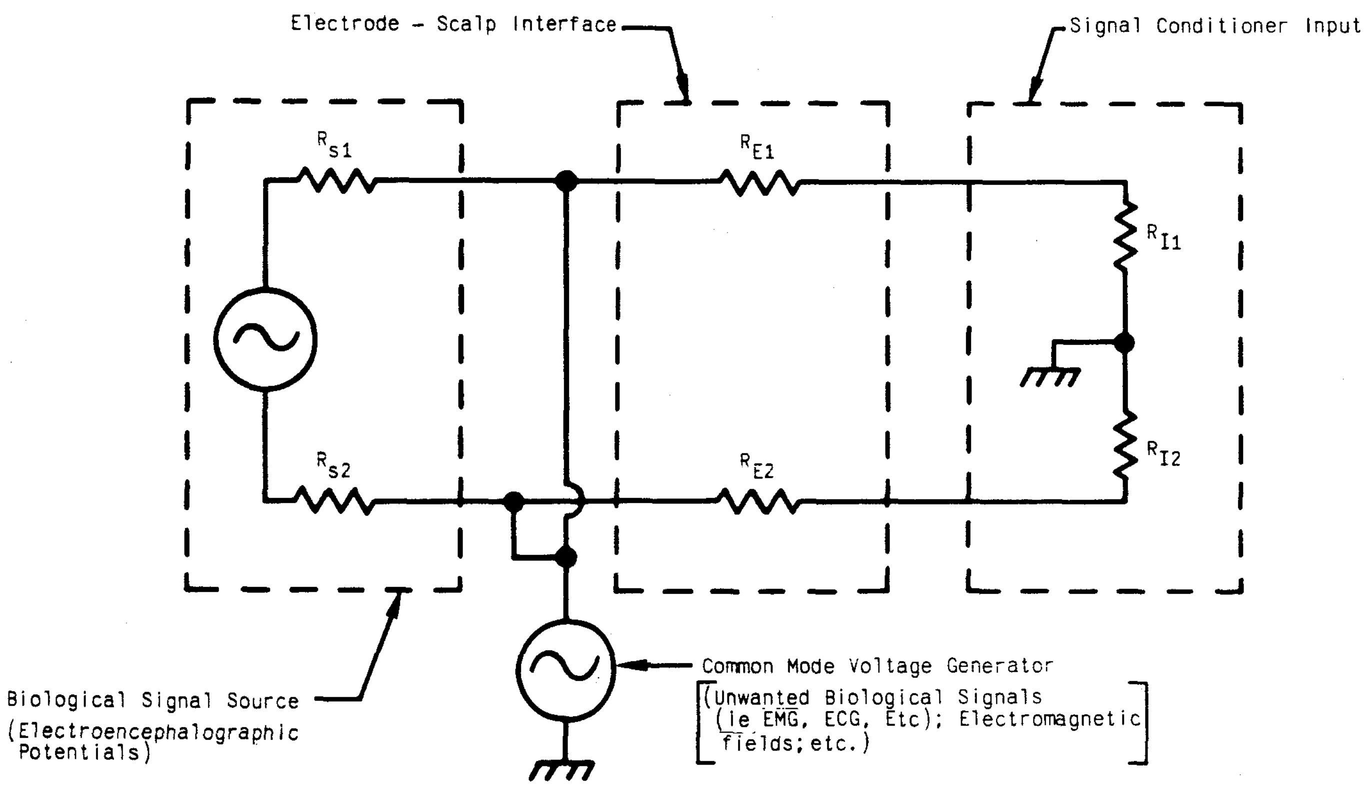


Figure 1-1. Equivalent Circuit, Simplified – Biological Signal, Common Mode Signal, Electrode Interface, and Signal Conditioner Input.

As can be seen, the biological signal source (which for the purposes of this discussion is meant to include only the electroencephalographic potentials, and not interfering potentials such as ECG, EMG, etc.) can be represented by a signal generator and two equivalent impedances, R_{S1} and R_{S2}, which represent the impedance of the signal paths from the neurons of the brain to the scalp. These impedances are actually complex, but for the purposes of this discussion can just as well be considered as simple resistances. Normally, R_{S1} and R_{S2} are equal, or at least their difference is so small as to be insignificant in this analysis.

The common mode voltage generator shown represents all common mode voltages which are generated within, or on the surface of the body, whether their cause is a biological function (i.e., ECG, EMG, etc.), or due to electromagnetic fields. Common mode voltages generated in the signal conditioner input leads are another phenomena, and will not be considered at this time.

R_{E1} and R_{E2} represent the impedances of the electrode-scalp interfaces, and although treated in this analysis as simple resistances, are in actuality quite complex. A detailed discussion of these impedances is too lengthy for presentation at this time, but is included in this report as Appendix II.

It has been empirically determined (J. L. Day and M. W. Lippitt, Jr.: A Long-Term Electrode System Suitable for ECG and Impedance Pneumography.) that R_{E1} and R_{E2} not only change in value with time by orders of magnitude, but change in an entirely unrelated manner. That is to say, that at any one moment, R_{E1} could be as much as 1/250, or 250 times the value of R_{E2}.

When one writes the transfer function describing the differential voltage developed at the signal conditioner input terminals as a function of the common mode voltage, it becomes apparent that this differential voltage increases quite rapidly as the input impedance is reduced (assuming $R_{E1} \neq R_{E2}$).

As an example, let us assign arbitrary values (which could realistically appear in an EEG system) to R_{E1}, R_{E2}, R_{I1}, R_{I2}, and the common mode voltage (E_{CM}) as follows:

$$R_{E1} = 150 \times 10^3 \text{ ohms}$$

$$R_{E2} = 50 \times 10^3 \text{ ohms}$$

$$R_{I1} = R_{I2} = 5 \times 10^6 \text{ ohms}$$

$$E_{CM} = 10 \text{ mv peak to peak}$$

The expression for the differential voltage (E_{DIFF}) which results is as follows:

$$E_{DIFF} = E_2 - E_1, \text{ where: } E_2 = E_{CM} \frac{R_{I2}}{R_{I2}+R_{E2}}, \quad E_1 = E_{CM} \frac{R_{I1}}{R_{I1}+R_{E1}}$$

$$E_{DIFF} = E_{CM}\left[\frac{R_{I2}}{R_{I2} + R_{E2}} - \frac{R_{I1}}{R_{I1} + R_{E1}}\right]$$

$$= 10 \text{ mv}\left[\frac{5 \times 10^6}{5.05 \times 10^6} - \frac{5 \times 10^6}{5.15 \times 10^6}\right] = 10 \text{ mv } (.990099 - .970837)$$

$$= 192.6 \text{ microvolts peak to peak.}$$

Signals of this magnitude would completely obscure the desired EEG signals, which range typically from 30 to 100 microvolts.

If the input impedance of the amplifier (R_I) were assumed to be infinite, it is obvious that this differential voltage would now become zero.

It is also interesting to note that using the Beckman EEG signal conditioner, which has an input impedance of 500 megohms (nominal) at 60 cps, the resulting differential voltages under the otherwise identical conditions would be <u>2.0 microvolts</u> peak-to-peak, which is insignificantly small compared to the EEG signal magnitude.

Another interesting facet of a high input impedance is that the input impedances (R_{I1} and R_{I2}) can be severely mismatched with little or no detriment of performance. As an example, let us assume that R_{I1} = 400 megohms, and R_{I2} = 800 megohms. The resulting differential voltage under the same conditions as before would now be 3.1 microvolts peak-to-peak, which again is insignificantly small.

Direct coupling is desirable from two standpoints; it eliminates another source of unbalanced impedances between the signal source and the amplifier input (coupling capacitors), and it eliminates the need for having resistors connected between the amplifier input and ground for biasing purposes, which would typically lower the input impedance to 22 megohms or less (due to size limitations of resistors). The direct coupled amplifier does not need input biasing resistors, as it picks up its ground reference through the subject.

Common mode rejection ratio is a measure of the ability of an amplifier to reject large common mode signals present <u>at the input terminals</u>. These signals are normally induced either within the subject, on the subject, or in the leads which connect the subject to the amplifier input.

Since there are always fields of this nature present, it is advantageous for an amplifier to be able to discriminate against them. Although infinite values of common mode rejection ratio would completely eliminate the undesirable effect of these signals on the required low level signals, finite values are adequate if they are high enough. For example, an amplifier with a common mode rejection ratio of 100 db (such as the Beckman EEG signal conditioner) would suppress a common mode voltage of 0.5 volts to the extent that the resulting interfering signal would appear to be only 5 microvolts.

Noise, which is a form of artifact, can be defined as an extraneous signal which is superimposed upon the biological signal. Noise signals can be generated within the amplifier itself, or can be externally generated signals such as hum caused by inductive or capacitive pickup from external sources. Since the EEG potentials range from 30 to 100 microvolts, it is important that the noise be reduced to a minimum, preferably below 5 microvolts peak to peak.

The amplifier is designed to reject externally generated noise and to generate a minimum amount of noise internally.

A frequency response of 0.2 to 100 cps is necessary as the information content in the EEG rhythms extends over this frequency range.

Harmonic distortion must be kept to a minimum, as it would alter the electroencephalogram to the extent that it could change the interpretation, or at least make interpretation of the records more difficult.

A stable output is necessary to prevent the output signals from exceeding the channel limits of the on board recorder and/or telemetry system, as would happen if the output were allowed to drift.

The use of a low output impedance minimizes pickup problems in the cabling connecting the signal conditioner to the telemetry equipment and prevents loading by the telemetry channel. Furthermore, a more uniform amplifier response is obtained by minimizing capacitive effects of the cabling when used with a low impedance output.

2.0 Development Phase

The development phase of this program consisted of theoretical design and breadboard evaluation to verify that the design met the requirements as specified in paragraph 4.1 of the statement of work. Applicable sections of the statement of work are included in this report as Appendix I.

2.1 Theoretical Design Analysis and Breadboard Testing

A detailed design analysis was undertaken early in the program to determine the optimum circuit design consistent with the specific design objectives.

Many of these analysis are too complex to be presented in the body of this report, but are included as appendices for those interested. Only the conclusions are presented at this time.

2.1.1 Common Mode Rejection

Analysis of the common mode rejection (Appendix III) indicated that with normal component tolerances and no trimming adjustments, the common mode rejection ratio could be as low as 71 db (for worst case). It was therefore decided to add a trimming potentiometer to compensate for these tolerances. The breadboard tests verified our results, and showed that with addition of the trimming potentiometer, common mode rejection ratios in excess of 100 db could normally be achieved.

2.1.2 Recovery Time

Analysis of the signal conditioner (Appendix IV) was undertaken to determine the significant factors governing recovery time. This allowed us to determine the corrective steps available should they prove necessary.

The results of this analysis indicated that the recovery time could be made to conform to the requirements by use of dynamic range limiting (diodes).

A great deal of effort was expended on both analysis and design experiments to simultaneously achieve the desired frequency response and fast recovery time by use of non-linear diode dynamic range limiting. Diodes were obtained from many vendors and evaluated in the circuit, and many circuit configurations were tested. In every case, the results were the same: an improvement in recovery time could only be achieved at the expense of increasing the low frequency 3 db point.

An analysis was then undertaken to determine the relationship which existed between the low frequency 3 db point and recovery time for the circuit in question. This is included as Appendix V.

The results of this analysis indicated that the recovery time for a low frequency 3 db point at 0.2 cps would be equal to or slightly less than 15 seconds. Results of the breadboard testing verified that recovery time was typically 12 or 13 seconds.

The NASA was notified of this, and agreed that 15 seconds was an acceptable time for recovery.

2.1.3 Input Impedance

Analysis of the signal conditioner input circuit indicated that the gate-to-source capacitance would determine the minimum input impedance, and that using almost any good quality FET pair, this value would always be above 100

Megohms. Breadboard tests, and subsequent acceptance testing showed the input impedance to be nominally 3000 megohms at 2 cps, 600 megohms at 20 cps, and 110 megohms at 100 cps. The work statement specifies that the input impedance shall be greater than 5 megohms.

2.1.4 Input Unbalance

The input unbalance is determined by the amount of leakage current flowing in the FET gates. This current is specified by the manufacturer to be less than 0.25 nanoamperes. The work statement specifies that leakage current shall be less than one microampere. Breadboard and acceptance test results have shown this leakage current to be so low as to be immeasureable with standard laboratory equipment.

2.1.5 Output Impedance

The output impedance requirements were met by using an emitter follower output stage. This stage provides an output impedance of less than 500 ohms from each side to ground, and less than 1000 ohms between differential output terminals.

2.1.6 Output Offset

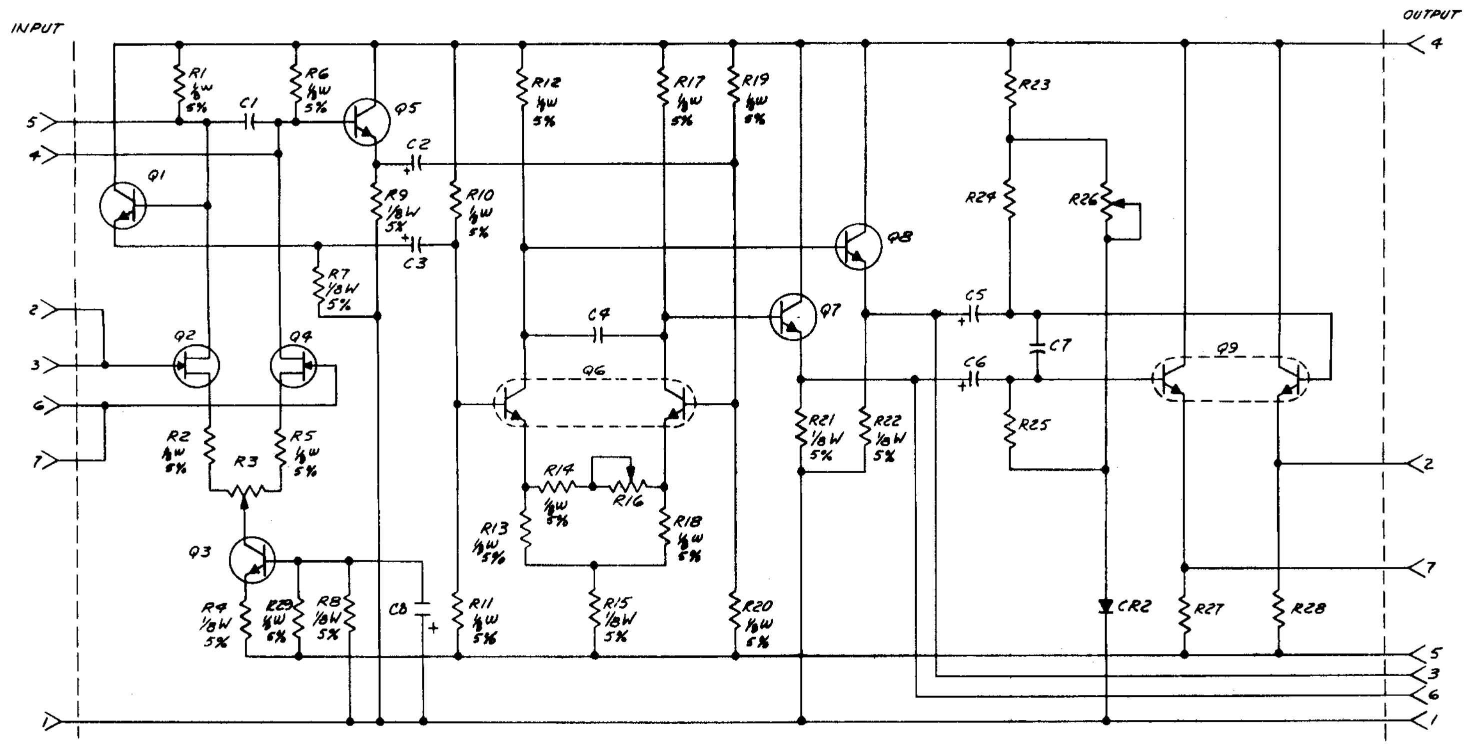
The 10 mv ± 2% output offset over the specified operating temperature range was achieved by selecting a transistor pair for Q_9 (reference figure 2-1) which had a $\Delta V_{BE}/\Delta T$ less than ± 0.2 mv over the required temperature range (ΔT). The transistor pair selected has a maximum $\Delta V_{BE}/\Delta T$ of 5 microvolts per °C. Since the required operating temperature range is 160°F (89°C), the maximum $\Delta V_{BE}/\Delta T$ is 0.445 mv, or ± .222 mv, which means that the transistor used for Q_9 had to be selected to have a $\Delta V_{BE}/\Delta T$ of less than 5 microvolts. This was accomplished by testing the various transistors in a dummy last stage over the required temperature range prior to welding, and selecting those transistors that met the output offset specifications. It developed that most of the transistors averaged 3.5 microvolts $\Delta V_{BE}/\Delta T$, and the selection process was thus easily accomplished.

The adjustment for the 10.0 mv offset is accomplished by the voltage divider action of R23 and R26. R26 must be adjustable because the initial ΔV_{BE} of the Q_9 transistor pair may differ by as much as ± 3 mv. R26 is large enough to provide an adjustment range of 0 to 20 mv, which is adequate for the specific requirements, and small enough to provide the necessary resolution.

2.1.7 Frequency Response

The required frequency response was readily achieved by selecting capacitors C2, C3, C5, and C6 to achieve the low frequency 3 db point at 0.2 cps, and capacitors C1, C4, and C7 (Figure 2-1) to achieve the high frequency 3 db point at 100 cps. The use of three capacitors to achieve the high

Beckman®



REF-RECEPTACLE PIN ASSIGNMENTS			
PIN	INPUT	PIN	OUTPUT
1	SIGNAL COMMON	1	POWER COMMON
2	INPUT A	2	OUTPUT A
3	INPUT A	3	TEST POINT
4	TEST POINT	4	+ 10 VOLTS DC
5	TEST POINT	5	- 10 VOLTS DC
6	INPUT B	6	TEST POINT
7	INPUT B	7	OUTPUT B

FIGURE 2-1. SCHEMATIC DIAGRAM, EEG SIGNAL CONDITIONER

frequency roll-off provided an attenuation rate of approximately 18 db per octave above 500 cycles, which suppresses the 50 KC signal by approximately 120 db (the 2 mv peak-to-peak signal would be reduced to an equivalent .002 microvolt signal referred to the amplifier input).

2.1.8 Harmonic Distortion

Analysis of the signal conditioner circuitry indicated that no harmonic distortion should occur under any of the specified operating conditions. Breadboard and acceptance test results verified that the harmonic distortion introduced by the signal conditioner is significantly less than the specified 1 percent.

2.1.9 Transient Response

Analysis of the signal conditioner operation indicated that the transient response was directly related to frequency response, and that with the specified frequency response, the transient response would be as specified. In effect, this amounted to a redundant specification of a single characteristic. Breadboard and acceptance test results verified that the transient response of the signal conditioner was within specifications.

2.1.10 Noise

The noise contribution of the input stage was the one characteristic that was not possible to analyze and predict.

This was true because of the extremely low frequency at which the signal conditioner was required to operate (0.2 cps), and the lack of noise data on field effect transistors in this frequency region.

A brief word explaining the noise problem is pertinent to an understanding of how it got to be a problem in the first place, and is as follows:

The NASA request for proposal specified that the maximum permissible noise voltage referred to the amplifier input could be 7 microvolts peak-to-peak over the frequency range of 0.5 to 100 cps. Beckman proposed to deliver a signal conditioner with only 5 microvolts peak-to-peak noise over this frequency range based on the results of previous tests.

Subsequent to contract negotiations, after agreement on all cost and technical matters, but prior to final execution, NASA contacted Beckman Instruments, Inc. by telephone to request a change in the low end 3 db point from 0.5 cps to 0.2 cps. The effect this would have on the noise level was impossible to predict, but after discussing the problem with manufacturers of field effect transistors (who know very little about the $^{1}/F$ noise characteristics of their devices in this frequency range), it was decided that the probability that the noise specification could be adhered to with the frequency change requested by the NASA was good enough to warrant accepting the change. As it developed, that conclusion was ill advised, as months were subsequently spent in an endeavor to meet the noise specification over the revised frequency band.

The silicon planer stages of the signal conditioner were optimized for low noise operation (i.e. they were operated at the current level determined to provide minimum noise), and a selection process was then established to find the lowest noise field effect transistors available.

Field effect transistors were purchased from practically all of the major transistor manufacturers and evaluated in the circuit. The lowest noise level achieved by this process was approximately 6 microvolts peak-to-peak (on the breadboard configuration). It was felt, however, that welded connections, shorter conductor paths, and the stainless steel enclosure might reduce this noise somewhat, so a decision was made to fabricate the first qualification unit.

Results of the tests performed on this unit verified that the noise was indeed reduced to below 5 microvolts, and the decision was made to fabricate the second qualification unit and proceed with the qualification test phase of the program.

2.1.11 Gain

It was evident after analyzing the circuit requirements that a gain control would have to be employed which would vary the gain of each half of the differential amplifier in a symmetrical manner. To achieve this result, resistors R13, R14, R18, and potentionmeter R16 were connected in a wye configuration as shown in Figure 2-1. These resistors are also selected to provide a minimum gain of 100 and a maximum gain of 150.

The amplifier was thoroughly tested with 0.3 volt differential offset at the input, and conformed to the specifications with one minor exception. The gain decreased slightly when the offset voltage got above 0.2 volts (reference Figure 2-2). Inasmuch as the gain rolloff is very slight, and only occurs with offset voltages above 0.2 volts, it is felt that it is not significant and thus should be acceptable.

2.1.12 Gain Stability

Gain stability is achieved through use of negative feedback applied to the transistor emitters (and sources) of the gain stages. Breadboard and acceptance test results show the gain to vary less than 1% over any 12 hour period at an ambient temperature of 75°F ±10°F.

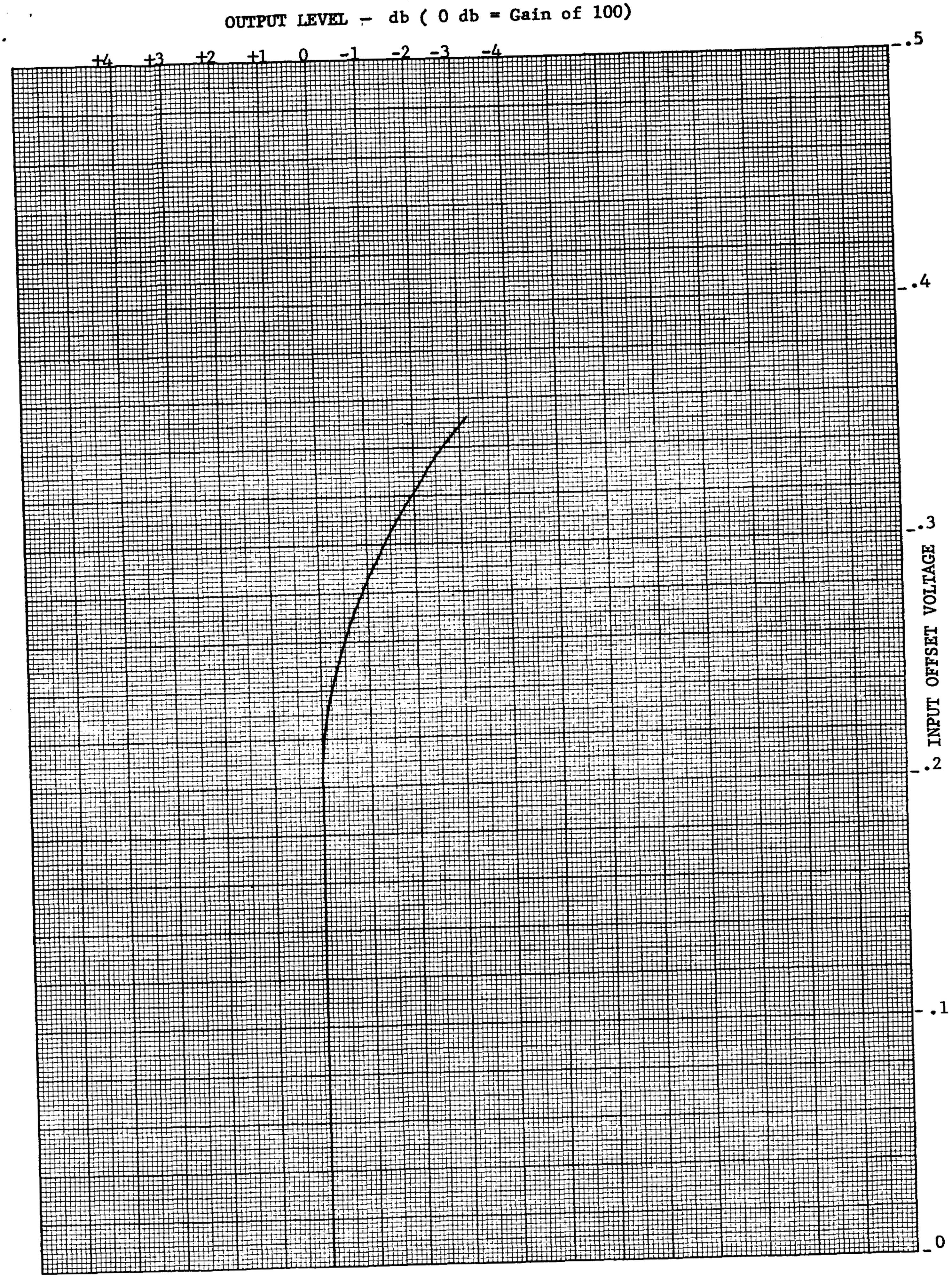


FIGURE 2.2. Normalized Gain vs. Input Offset Voltage

2.1.13 Power Consumption

Low power consumption was achieved by careful selection of transistors having the necessary performance characteristics at very low current levels, and by careful circuit design to prevent unnecessary current consumption.

The field effect transistors, Q_2 and Q_4, operate with a current of approximately 100 microamperes each. Transistor Q_3 supplies current for Q_2 and Q_4, and uses no additional current. Transistors Q_1, Q_5, Q_7 and Q_8 operate at approximately 10 microamperes each. Transistor pair Q_6 operates with a current of approximately 100 microamperes per side, with an additional 1 ma from each supply being used in the bias network for this stage. Transistor pair Q_9 operates with a current of approximately 100 microamperes per side, with an additional 100 microamperes from the +10 volt supply being used through resistor R23 and potentiometer R26 to provide the +10 mv output offset bias point. Total current consumption for the entire signal conditioner is approximately 1.6 ma from each supply, considerably below the specified 5 ma maximum.

3.0 FABRICATION OF QUALIFICATION AND FLIGHT UNITS

3.1 Size

In order to meet the contract requirements regarding size, it was necessary to use welded cordwood construction techniques and miniature components. Figure 3-1 is a photograph showing two signal conditioner welded assemblies prior to encapsulation. No problems were encountered and the size restrictions were adhered to.

3.2 Weight

It was determined that encapsulating the signal conditioners with solid epoxy would cause the weight to exceed the specification by approximately 10 grams. A decision was therefore made to encapsulate the signal conditioners with a foam RTV, which is extremely light and still provides the necessary protection against shock and vibration. The ends of the signal conditioner (where the connectors protrude) are sealed with a layer of solid epoxy approximately 0.1 inch thick to act as a moisture barrier.

3.3 Susceptibility to Electrical Interference

To minimize the susceptibility of the signal conditioner to electrical interference, it was decided to enclose the circuitry in a continuous stainless steel case, with the case being connected electrically to circuit ground. This has proven to be very effective as evidenced by the ability of the signal conditioner to pass the stringent qualification tests.

Beckman®

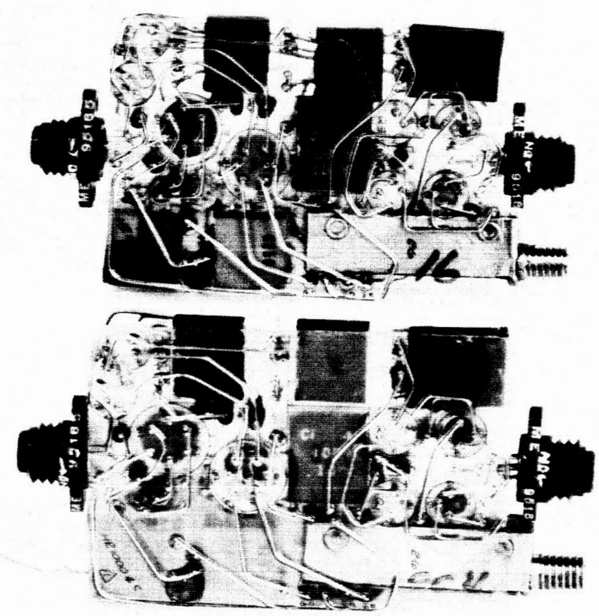


FIGURE 3-1. EEG WELDED ELECTRONIC ASSEMBLIES

3.4 Noise

Although the noise problem appeared to have been solved during the development phase of the program, as reported in Section 2.1.10 of this report, it developed that some of the production signal conditioners exhibited excessive noise during the post-weld testing.

This problem was discussed with the manufacturer of the field effect transistors, and it was decided that excessive gate leakage was the most probable cause of the problem. New field effect transistors were then ordered with tighter leakage specifications and installed in the signal conditioners. Subsequent testing showed that the noise was reduced to within contract specifications on only two-thirds of the signal conditioners. The other signal conditioners still exhibited a noise level in excess of the contract specifications.

The field effect transistor manufacturer was again contacted, and advised of the situation. It was concluded at this time that a 100% yield could probably not be achieved by ordering transistors to the manufacturer's specifications. The field effect transistor manufacturer then supplied Beckman with 100% more transistors than were needed, to enable selection of the lowest noise units.

If additional units are ever to be built, it is recommended that a tighter noise specification be added to the transistor specifications to insure that the signal conditioners have sufficiently low noise.

4.0 QUALIFICATION TESTING

Due to the extensive nature of the qualification test program, part of the testing was conducted in the Beckman Corporate Reliability Laboratories, while the remainder was subcontracted to outside testing laboratories. The qualification tests consisted of subjecting signal conditioners to the following environments:

1. Electrical and Electronic Interference, Susceptibility: Paragraph 4.3.4.1.1 and 4.3.4.2, MIL-I-26600.
2. High Temperature: MIL-E-5272, Procedure II.
3. Low Temperature: Procedure I, -60°F storage - 4 hours; 0°F operational - 4 hours; Procedure II, -15°F storage - 4 hours; 0°F operational - 4 hours.
4. Humidity: MIL-E-5272, Procedure I.
5. Acceleration: Maximum acceleration, 15.7 g's.
6. Sand and Dust: MIL-E-5272, Procedure I.
7. Acoustic Noise: 20 cps to 10,000 cps, over-all SPL-135 db (re: 0.0002 dyne/cm^2).
8. Random Vibration: 20 cps to 2000 cps, over-all level, 8.8 g (rms).
9. Shock: 11 to 40 g's, 11 millisecond duration, 12 shocks.
10. Pressure and Oxygen Atmosphere: 1.0 psia and 19 psia, 160°F, 1.5 hours each; 100% oxygen atmosphere, 160°F, 40 hours.

11. Endurance Test: 336 hours operation at 130°F.

12. Salt Spray: Method 509, MIL-STD-810.

Two units were to be qualification tested as specified in the statement of work. Due to unforeseen delays in the test program caused by signal conditioner failures, however, two additional units were incorporated into the test program with the approval of the NASA Technical Monitor.

The signal conditioners met all test requirements during high temperature, salt spray, pressure, oxygen atmosphere, acceleration, sand and dust, acoustic noise, shock, and endurance on the first attempt.

The failure which occurred during electrical interference tests was caused by a conflict in test requirements between MIL-I-26600 and the Statement of Work. After the test procedure had been modified, incorporating the Statement of Work precedence over subsidiary specifications, successful compliance to these test specifications was seen during a retest.

Two failures of two separate units were encountered during the low temperature tests. Prior to the test of the third unit, however, the temperature requirements were relaxed from -60°F to -15°F. Tests of the third unit to these new requirements resulted in successful compliance to test specifications.

During humidity tests, one unit failed on two separate occasions. Both of these failures were found to be due to inadequate hermetic seals. After improved sealing techniques were employed, successful completion of the humidity test was accomplished using a second unit.

During the vibration test and two repeats thereof, increases in the output noise characteristics were seen reaching levels approximately twice the maximum allowable at approximately 1 mv peak-to-peak. Although the output noise level did not satisfy operational requirements during vibration, it is felt that the vibratory inputs of the test were not representative of those which will prevail during actual flight. During the vibration test, the EEG unit was hard mounted to the vibration table. During the actual flight environments, the units will be mounted in intimate contact with the astronaut.

At the completion of the test program, notification was given by the NASA Technical Monitor that the noise requirement during vibration was relaxed to 2 mv (20 μv referred to the input). Therefore, satisfactory compliance to these new requirements was demonstrated.

The failure that occurred during the immersion test was also due to the lack of a proper hermetic seal as reported above for humidity tests. After the unit had been modified to reflect the improved method of encapsulation mentioned, a successful completion of the test was seen.

The Qualification Test Report is contained in a separate document which the reader may refer to for more complete details. The report is Beckman Report No. 367, "Qualification Test Report, Electroencephalogram Signal Conditioner."

APPENDIX I

Exhibit "A"

STATEMENT OF WORK

Electroencephalogram Signal Conditioner

4. DESIGN REQUIREMENTS: The system shall be capable of meeting the following requirements under any combination of the environmental conditions of paragraph 4.3 herein. MIL-E-8189 shall be the applicable general specifications.

4.1 Electrical Requirements

4.1.1 Input

4.1.1.1 The magnitude of the input impedance measured between differential input terminals shall be not less than 5 megohms over the frequency range 0.2 to 100 cps. The magnitude of the input impedance measured from one differential input terminal to ground shall not differ from the magnitude of the input impedance measured from the other differential input terminal to ground by more than 1% over the frequency range 0.2 to 100 cps.

4.1.1.2 The input circuit shall be d-c coupled and designed in such a way that existing circuit unbalances do not produce a current flow in excess of 1×10^{-6} amperes in source impedances ranging from 5,000 ohms to 40,000 ohms.

4.1.1.3 With the exception of common mode rejection ratio (paragraph 4.1.6) the amplifier shall operate within all specifications with a 0.3 volt d-c potential of either positive or negative polarity applied differentially in series with the input signal.

4.1.1.4 The amplifier must operate within the specifications with a source impedance of 0-40,000 ohms connected to the differential input terminals.

4.1.2 Output

4.1.2.1 The magnitude of the output impedance shall be not greater than 500 ohms measured from either output terminal to ground. Filtering shall be such that a rolloff of 6 db per octave at 100 cps is obtained.

4.1.2.2 With a zero input signal, output shall be biased at 10 mv ±2%. With input signals, output shall then be ±10 mv around the 10 mv biased point. Therefore, output is always unipolar from 0 to 20 mv.

4.1.3 Frequency Response

4.1.3.1 The frequency response of the amplifier shall be such that the upper and lower 3 db points are respectively 100 cps and 0.2 cps.

4.1.3.2 The unit shall be designed to be insensitive to the presence of a 2 mv, p-p, 50.0 KC ±10 KC sinusoidal signal applied to the differential input terminals of the amplifier.

4.1.4 Harmonic Distortion

4.1.4.1 The harmonic distortion shall be less than 1% over the frequency range 0.2 cps to 100 cps.

4.1.5 Transient Response

4.1.5.1 A 5 cps square wave of 50% full scale amplitude shall overshoot less than 5% and shall droop no more than 11.8%.

4.1.6 Common Mode Rejection

4.1.6.1 An 80 db common mode rejection ratio is desirable and less than 60 db shall not be acceptable (0.2 cps-100 cps) with a 0.3 volt d-c potential of either positive or negative polarity applied differentially in series with the input signal. The contractor shall endeavor to meet 100 and 80 db.

4.1.7 Recovery Time

4.1.7.1 Recovery time after transient inputs of up to one volt for 100 milliseconds or less shall not be greater than 15 seconds.

4.1.8 Noise

4.1.8.1 The maximum permissible noise voltage referred to the input of the amplifier shall be 5 micro volts, peak-to-peak.

4.1.9 <u>Gain</u>

4.1.9.1 The adjustable voltage gain shall be 100-150.

4.1.10 <u>Gain Stability</u>

4.1.10.1 The gain shall not vary more than ±5% over any 12 hour period at an ambient temperature of 75 degrees F ±10 degrees after ten (10) minutes of warmup.

4.1.11 <u>Power</u>

4.1.11.1 Prime power supplied to unit from capsule power source will be +10 volts, d-c and -10 volts, d-c ±1%. Ripple and noise will not exceed 0.01%.

4.1.11.2 Ripple content will not exceed .01%.

4.1.11.3 Current consumption shall be as small as practical and no greater than 5 ma from each supply.

4.2 <u>Physical Requirements</u>

4.2.1 <u>Weight</u>

The weight of the conditioner shall not exceed 45 grams.

4.2.2 <u>Dimensions</u>

Physical dimensions of the signal conditioner shall not exceed 2.3 inches by 1.5 inches by 0.390 inches.

4.2.3 <u>Gain Control</u>

The unit shall have a gain control accessible from the end when the connectors are attached. Clockwise rotation shall result in increasing gain.

4.3 <u>Environment</u>: The equipment shall be capable of performing satisfactorily during launch, orbit, reentry, and impact in accordance with the total requirements of this specification when subjected to any natural combination of the environments specified herein.

4.3.1 <u>Salt Sea Atmosphere</u>: The equipment shall be capable of operation in a salt sea atmosphere as specified in paragraph 5.3.1.7 herein.

4.3.2 <u>Salt Water Immersion</u>: The equipment shall be capable of operating continuously while subjected to an immersion test as specified in paragraph 5.3.1.12 herein.

4.3.3 Sand and Dust: The equipment shall be capable of operation in a sand and dust atmosphere as specified in paragraph 5.3.1.6 herein.

4.3.4 Fungus: The equipment shall be capable of operation after being subjected to ambient conditions conducive to fungus growth as specified in paragraph 5.3.1.5 herein.

4.3.5 Pressure: The equipment shall be capable of operation while being subjected to ambient pressure variations from 1.0 to 19.0 psia.

4.3.6 Temperature: The equipment shall be capable of operation while being subjected to ambient temperature from 0° F. to +160°F. The equipment shall withstand, without damage, nonoperational exposure to ambient temperatures of +200°F. and -60°F.

4.3.7 Humidity: The equipment shall be capable of operation both during and after subjection to variations in relative humidity from 15 percent to 100 percent.

4.3.8 Acceleration: The equipment shall be capable of operation both during and after subjection to the acceleration specified in paragraph 5.3.1.8 herein.

4.3.9 Shock: The equipment shall be capable of operation after being subjected to shock as specified in paragraph 5.3.1.9 herein.

4.3.10 Vibration: The equipment shall be capable of operation while being subjected to random vibration as specified in paragraph 5.3.1.10 herein.

4.3.11 Electrical and Electronic Susceptibility: The equipment shall be completely unaffected by conducted or radiated signals as defined in MIL-I-26600.

4.3.12 Acoustic Noise: The equipment shall be capable of operation while being subjected to acoustic noise as specified in paragraph 5.3.1.11 herein.

4.3.13 Oxygen Atmosphere: The equipment shall be capable of operation in a 100 percent 0_2 atmosphere without any deleterious effects to the equipment and without emission of either toxic or obnoxious odors.

4.3.14 Rain: The equipment shall be capable of withstanding a rainy atmosphere as described in MIL-E-5272.

4.3.15 Temperature - Altitude: The equipment shall be capable of operation while being subjected to any combination of temperature-altitude as specified herein.

4.3.16 Voltage Variation: Operation of the equipment shall be unaffected when subjected to voltage variations within the limits of paragraph 4.3 herein.

5. TEST REQUIREMENTS

5.1 Classification of Tests: The equipment shall be subjected to the following tests which shall be conducted by the Contractor. Specific test plans, procedures, and test results shall be prepared and submitted by the Contractor to NASA for approval.

5.1.1 Acceptance Tests: These tests are performed to assure that the materials, workmanship, and performance of units to be subjected to design approval tests or programmed for delivery to NASA are not faulty and that the units have been manufactured to approved drawings and specifications. These tests are normally an investigation of operating and nonoperating characteristics under room ambient environmental conditions.

5.1.2 Design Approval Tests: These tests are conducted on preproduction equipment to establish that the units comply with all the requirements of this Statement of Work. A complete test under operating environmental conditions is inferred.

5.2 Acceptance Tests

5.2.1 Examination: Each unit shall be examined to determine conformance with this exhibit with respect to materials, standard parts, and workmanship.

5.2.2 Testing: Each unit shall be tested to determine compliance with the detail functional requirements of Section 4.0 of this specification. These tests shall include, but are not limited to, the following:

a. Size
b. Weight
c. Input characteristics
d. Output characteristics
e. Power consumption
f. Noise referred to input.

5.3 Design Approval Tests: These tests shall be performed on the first production units. Release for production shall be based on satisfactory completion of these tests. Design approval testing shall consist of the qualification tests outlined herein. Prior to conducting these tests, each unit shall be subjected to, and shall meet the requirements of, the acceptance tests outlined in Section 5.2.

5.3.1 Qualification Tests: These tests shall be conducted by the Contractor and shall consist of the following tests. Two units shall be subjected to these tests; however, both units will not be required to undergo all tests. Sequence and distribution of tests shall be determined by Contractor subject to NASA approval.

5.3.1.1 Pressure: The equipment shall be placed in a chamber and the pressure reduced to 1.0 psia. The equipment shall operate satisfactorily with the chamber temperature at 160° F. for 1.5 hours. There shall be no crushing, distortion, opening of seals, or other damage deleterious to the proper operation, life and serviceability of the equipment as a result of this test. Repeat at 19.0 psia.

5.3.1.2 High Temperature: The equipment shall be subjected to Procedure II of the high-temperature test of Specification MIL-E-5272, except that operating time shall be continuous.

5.3.1.3 Low Temperature: The equipment shall be placed in the temperature chamber and the chamber cooled to -60° F. After four hours in this environment, the equipment shall be inspected for evidence of deterioration. The chamber temperature shall then be raised to and maintained at 0°F. After stabilization, the equipment shall be operated in this environment for a period of four hours.

5.3.1.4 Humidity: Per MIL-E-5272, Procedure I, except that operating time is continuous.

5.3.1.5 Fungus: Per MIL-E-5272, Procedure I, (applicable only to untreated and untested materials). This test need not be performed if a document is submitted stating that only nonnutrient materials are used.

5.3.1.6 Sand and Dust: Per MIL-E-5272, Procedure I. This test need not be performed if a document is submitted stating that the unit is sealed and that the external finishes have been subjected to Sand and Dust tests without detrimental results.

5.3.1.7 Salt Spray: Per MIL-STD-810 (USAF), Method 509.

5.3.1.8 Acceleration: Equipment shall be subjected to the test determined to be most stringent of those applicable to the equipment. Equipment shall be tested in each axis separately.

5.3.1.8.1 Launch: The equipment shall operate while receiving acceleration along an axis parallel to the longitudinal spacecraft axis (FWD) increasing linearly from 1g to 7.25g in 326 seconds.

5.3.1.8.2 Abort: The equipment shall be accelerated once in each direction along the three mutually perpendicular axes at 7.25g for one second, while operating. (Loads do not combine).

5.3.1.8.3 Reentry: The equipment shall be accelerated with a 15.7g resultant acceleration (15g longitudinal and 4.5g lateral) for 30 seconds in each direction along each of the two lateral axes at the 16.7° resultant angle while operating.

5.3.1.9 Shock: All shock tests shall be a half sine wave pulse of 11 ±1 millisecond duration.

5.3.1.9.1 Landing: Equipment shall operate satisfactorily following landing shock loads. The equipment shall be subjected to six landing impact shocks, one in each direction. These shocks consist of those loads shown in Figure 2.

5.3.1.9.2 Ultimate: Equipment shall be ultimate shock tested. Operation following the test is not required; however, the equipment shall not break loose from its mount. The equipment shall be subjected to six landing impact shocks, one in each direction. These shocks consist of those loads shown in Figure 3.

5.3.1.10 Vibration: The equipment shall operate within tolerance during and after the following test. The equipment shall be mounted to a rigid fixture capable of transmitting the specified vibration conditions and subjected to the input acceleration power spectral density shown on Figure 4, Curve I, through a load equalized shaker. Vibration testing shall continue for a period of 15 minutes along each of the three mutually perpendicular axes. No smaller than three sigma clippers shall be used in limiting acceleration peaks of the applied vibration.

5.3.1.11 Acoustic Noise: The equipment shall operate within tolerances while subjected to an overall sound pressure level with the distribution as indicated in Figure 5. The test duration shall be 30 minutes distributed in the three (3) most sensitive mutually perpendicular directions equally for 10 minutes per orientation. The most sensitive directions are defined as being those having the least amount of external structure between sensitive items and the noise source. If the power of the available facility is not sufficient to perform the entire wide band test, the spectra may be divided, with the approval of NASA, into a maximum of four (4) banks with 30 minutes testing in each band.

5.3.1.12 Immersion: The signal conditioner shall operate within specifications both during and after the following test:

a. Immerse the signal conditioner (and electrical connectors) in urine for two (2) hours.
b. Remove the unit and expose it to 100% O_2 at 5 psia and 160°F. until dry.
c. Spray the unit with urine until saturated and allow it to dry. Continue alternately spraying and drying at 160°F. (with no cleaning between tests) for 40 hours.
d. At the end of the "Spray-Dry" cycling, the uncleaned unit must operate normally at 100% O_2, 5 psia and 160°F. in 95% relative humidity. *
e. Without cleaning, submit the unit to the test of paragraph 5.3.1.15 herein.

*Above environments should be to ±5% accuracy, except RH which shall be at $95 {}^{+5}_{-0}\%$.

5.3.1.13 Oxygen Atmosphere: The equipment shall be placed in an atmosphere of 100 percent oxygen, at ambient pressure and operated for 40 hours. For at least two hours of this period, the chamber temperature shall be +160° F. Performance outside of specification tolerance, visible burning, creation of toxic gases, obnoxious odors, or deterioration of seals shall constitute failure to pass the test.

5.3.1.14 Electrical and Electronic Interferences: The equipment shall be tested in accordance with the susceptibility tests of MIL-I-26600.

5.3.1.15 Endurance Test: One unit shall be subjected to an endurance test which shall be conducted at ambient pressure and at least 120° F. for 336 hours. During this time, the unit shall be operating with simulated input signals and normal output signals.

APPENDIX II

2.6.2 Biopotential Electrode Theory

A biopotential electrode is often considered to be a simple electrical connection to the subject. This is not strictly true, since the electrode must convert a flow of ions in tissue to an analogous flow of electrons within a metallic conductor. In this respect, the biopotential electrode is a complicated transducer which must convert energy from one form to another without losing information content. The ion flow is converted to a flow of electrons by electrochemical reactions taking place at the electrode-tissue interface. Each electrode may be considered a half-cell battery which generates an electrical potential difference between the metallic electrode and the tissue.[24] The magnitude of the potential is determined by the nature of the metal of the electrode and by the type and concentration of ions present at the tissue surface in the area of contact. This half-cell potential is typically less than one volt, but may reach a magnitude of three or more volts, and may be positive or negative.

2.6.3 Practical Biopotential Measurements

In practice, the measurement of small body currents would be very difficult with two simple metal electrodes because of the instability of the half-cell potential at either of the electrodes. The half-cell potential is dependent upon a chemical equilibrium determined by the concentration of metal ions in the solution in the immediate vicinity of the electrode. This concentration is significantly higher at the electrode than anywhere else in the electrolyte solution, and any disturbance which would change the metal ion concentration at the interface would change the half-cell potential in an analogous manner.

For example, if the electrode were moved, tapped, or slightly jiggled, the solution would be disturbed at the interface, moving some of the metal ions into thesolution and changing the half-cell potential accordingly. Such a system is very susceptible to motion artifacts and would be unstable when used to make DC and low frequency measurements. While ideally no potential difference should exist between a pair of identical electrodes, it is not uncommon to measure 20-50 millivolts potential difference when silver electrodes are applied to tissues.

When an electrode half-cell potential is modified by a changing concentration of ions at the interface, due either to a flow of current through the electrodes or due to local chemical conditions, the electrode is said to be "polarized".[24] An electrode which is severely polarized will actively impede the current at low frequencies and tends to act as a filter. This results in an altered frequency response and signal distortion.

The chemical reaction responsible for the electrode half-cell potential may be represented by the generalized chemical equation,

$$M = M^{+} + e^{-}$$

Using the Nernst equation, the potential developed by the electrode and the ions in the gel is:

$$E = E^{o} + \frac{RT}{F} \log (M^{+})$$

where,

E = observed potential

E^o = standard potential for half cell

R = gas constant

T = absolute temperature

F = coulombs per equivalent

M^+ = ions present (molar concentration)

Table 2-3 gives the standard electrode potentials of various elements; it is customary to assign the zero potential to the hydrogen electrode.

TABLE 2-3

ELECTROMOTIVE SERIES FOR SOME ELECTRODES

Electrode	Half Reaction	Electrode Potential (volts)
Lithium	$Li = Li^{+} + e^{-}$	3.02
Potassium	$K = K^{+} + e^{-}$	2.92
Sodium	$Na = Na^{+} + e^{-}$	2.71
Magnesium	$Mg = Mg^{++} + 2e^{-}$	2.34
Aluminum	$Al = Al^{+++} + 3e^{-}$	1.67
Zinc	$Zn = Zn^{++} + 2e^{-}$	0.76
Iron	$Fe = Fe^{++} + 2e^{-}$	0.44
Cadmium	$Cd = Cd^{++} + 2e^{-}$	0.40
Nickel	$Nl = Nl^{++} + 2e^{-}$	0.25
Tin	$Sn = Sn^{++} + 2e^{-}$	0.14
Lead	$Pb = Pb^{++} + 2e^{-}$	0.13
Hydrogen	$H_2 = 2H^{+} + 2e^{-}$	0.00
Copper	$Cu = Cu^{++} + 2e^{-}$	-0.34
Silver	$Ag = Ag^{++} + 2e^{-}$	-0.80
Platinum	$Pt = Pt^{++} + 2e^{-}$	-1.20
Gold	$Au = Au^{+++} + 3e^{-}$	-1.42
Ag, AgCl, Cl^{-}	$Ag + Cl^{-} = AgCl + e^{-}$	-0.22

Since silver is often used as a biological electrode material, it is interesting to examine the consequences of placing a silver electrode in contact with tissue. It may be assumed that a pure silver electrode, whose surface is covered with a thin coating of silver oxide, is placed in contact with an electrolytic solution containing a known concentration of sodium and chloride ions. In this model, after initial contact, the small amount of silver oxide at the surface begins to dissolve to produce a small concentration of silver chloride in the solution. The existence of silver ions in solution at the surface of the metallic silver is responsible for the generated half-cell potential.

For the silver electrode the Nernst equation reduces to:

$$E = E^{o} + .0591 \log (Ag+) \quad (\text{at } 25^{o}C)$$

If another identical electrode would be placed in the solution, it would develop an identical half-cell potential. If an ideal voltmeter was used to measure the difference between the two electrodes, no difference would be observed, since the two half cells would be identical and oppose each other in the circuit. If an electrical generator (e.g., the heart) were located in the solution, some distance away from the position of the electrodes, the electrode potential difference would be only due to the generator, and thus the electrodes would be capable of measuring the small ion currents produced by the generator.

The term "polarization", when applied to biological electrodes, is usually used to describe changes in electrical potential developed by the electrode-tissue interface. In applications where significant currents flow through the electrodes (as in impedance pneumography) "polarization" refers to the various changes caused by the current flow. These changes may be classified in three categories. The first are changes caused by irreversible decomposition processes where metal or gaseous ions are removed from the solution. These are encountered at low current densities. The second polarization process occurs when the rate of ion production or utilization exceeds the rate of diffusion of these ions in the solution, causing a concentration gradient. Higher current densities are necessary to produce this type of potential shift. The third category simply includes voltage changes at the electrodes due to their resistance and the current flowing through them. All three of these polarization processes occur at electrodes where significant current flows, such as when electrodes are used for stimulating tissues, or during bio-impedance measurements.

An electrode can develop artifact signals often indistinguishable from polarization effects under circumstances not necessarily caused by the flow of electrical current. The potential developed by the electrode may be affected by chemical changes at or near the metal-electrolyte interface, which alter the concentration of the metallic ion. This is sometimes called "chemical polarization". In general, the difficulties encountered in the use of electrodes in measuring biopotentials are more likely the result of these local electrochemical effects than of true current polarization.

APPENDIX III

DIFFERENTIAL FIELD EFFECT TRANSISTOR AMPLIFIER ANALYSIS

I. Common-Mode Rejection

The common-mode rejection ratio is often erroneously considered to be simply the ratio of differential to common-mode gain. In practice, the common-mode rejection ratio is limited due to circuit unbalances. In this analysis, we derive the usual expressions for small signal differential amplifier gain and, by the method of Middlebrook,[1] derive an expression for the largest common-mode rejection ratio possible in the presence of simultaneous circuit unbalances in r_p and g_m.

Circuit　　　　　　　　　　A-C Model

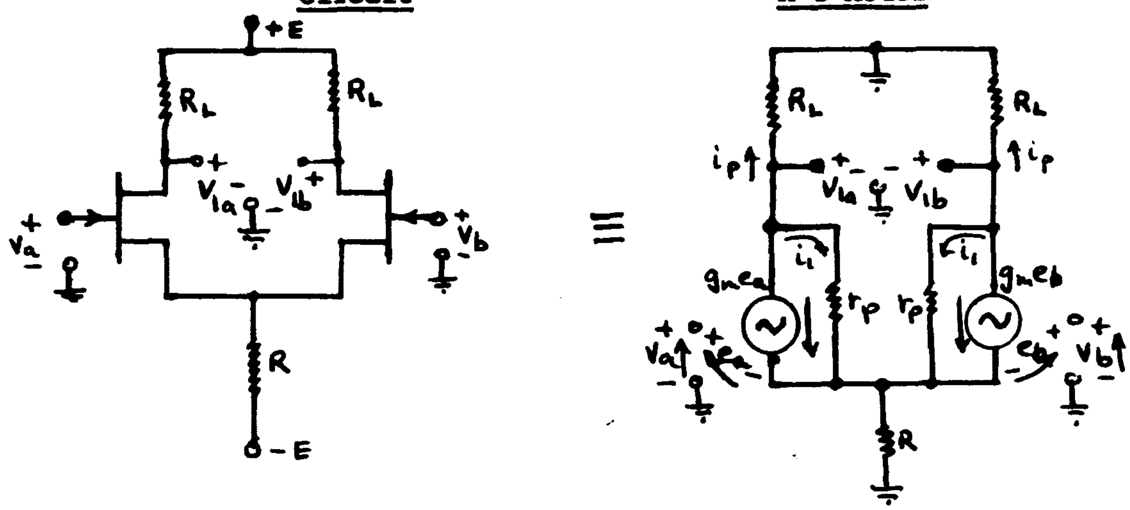


Figure One - F.E.T. Amplifier and Model

[1]Middlebrook, R.D. Differential Amplifiers, Wiley & Sons, New York, 1963.

For differential input signals, the voltage across R does not change and it may be replaced by a short circuit. The following model then applies:

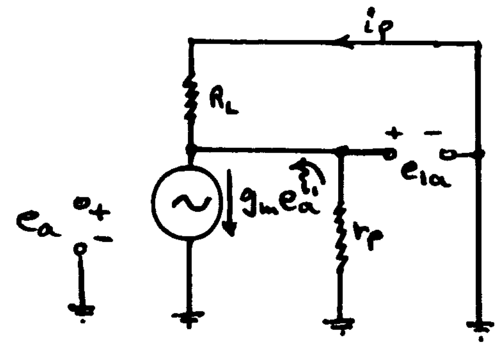


Figure Two: Model for Differential Input Signals

Once having observed relations (1), (2), and (3), the analysis is simple.

$$e_{1a} = -i_p R_L \quad (1)$$
$$i_1 = -e_{1a}/r_p \quad (2)$$
$$g_m e_a = i_1 + i_p \quad (3)$$
$$i_1 = g_m e_a - i_p \quad (4)$$
$$g_m e_a - i_p = -\frac{e_{1a}}{r_p} \quad (5)$$
$$-i_p = \frac{-e_{1a}}{r_p} - g_m e_a \quad (6)$$
$$e_{1a} = -R_L\left[\frac{e_{1a}}{r_p} + g_m e_a\right] \quad (7)$$
$$e_{1a}\left[1 + \frac{R_L}{r_p}\right] = -g_m e_a R_L \quad (8)$$
$$\frac{e_{1a}}{e_a} = \frac{-g_m R_L}{1 + \frac{R_L}{r_p}} \quad (9)$$

Thus, the differential gain is given by,

$$\frac{e_{1a} - e_{1b}}{e_a - e_b} = \frac{-g_m R_L}{1 + R_L/r_p} \quad (10) \quad \text{or,} \approx -g_m R_L \text{ for } R_L \ll r_p \quad (11)$$

The following model holds for common-mode signals.

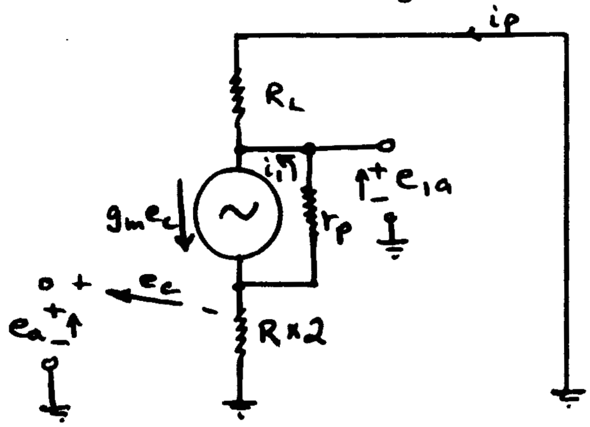


Figure Three, Model for Common-Mode Input Signals

Because R is now included, another mesh is introduced into the model and an additional equation is required. Note that the value of R is doubled as two identical common-mode currents flow through it. The analysis proceeds as follows:

$$e_{1a} = -i_p R_L \qquad (12)$$

$$g_m e_c = i_1 + i_p \qquad (13)$$

$$e_c = e_a - i_p 2R \qquad (14)$$

$$e_{1a} = -i_1 r_p + i_p \cdot 2R \qquad (15)$$

$$g_m (e_a - i_p \cdot 2R) = i_1 + i_p \qquad (16)$$

$$i_1 = g_m (e_a - i_p \cdot 2R) - i_p \qquad (17)$$

$$-i_1 = \frac{e_{1a} - i_p 2R}{r_p} \qquad (18)$$

$$-g_m (e_a - i_p \cdot 2R) + i_p = \frac{e_{1a} - i_p 2R}{r_p} \qquad (19)$$

$$i_p = \frac{\frac{e_{1a}}{r_p} + g_m e_a}{\left(\frac{2R}{r_p} + g_m \cdot 2R + 1\right)} \qquad (20)$$

$$e_{1a} = \frac{-R_L\left(\frac{e_{1a}}{r_p} + g_m e_a\right)}{\frac{2R}{r_p} + g_m \cdot 2R + 1} \qquad (21)$$

$$e_{1a}\left(1+\frac{R_L/r_p}{2R/r_p+g_m 2R+1}\right)=\frac{-R_L g_m e_a}{2R/r_p+g_m 2R+1} \tag{22}$$

$$\frac{e_{1a}}{e_a}=\frac{-g_m R_L}{\frac{2R}{r_p}+2g_m R+1+\frac{R_L}{r_p}} \tag{23}$$

We, thus, obtain the common-mode gain to be,

$$\frac{e_{1a}}{e_a}=\frac{-g_m R_L}{1+2g_m R+\frac{2R+R_L}{r_p}} \quad (24) \qquad \text{or,} \approx \frac{-g_m R_L}{1+2g_m R+2R/r_p} \quad \text{for } R_L \ll r_p \quad (25)$$

If we now define the common-mode "discrimination factor" to be the ratio of differential to common-mode gain, we obtain,

$$\text{Discrimination Factor} = 1+\left(\frac{2R+2Rg_m r_p}{r_p+R_L}\right) \tag{26}$$

Notice that for a balanced circuit, as $R \to \infty$, the discrimination factor $\to \infty$. This does not, however, imply that the c.m.r. $\to \infty$, as we shall show, when unbalances exist in the circuit.

To simplify our calculations, let us use the source transformation,

$$\mu = g_m r_p \tag{27}$$

By the method of Middlebrook, we may then compute the effects of unbalanced g_m and r_p values on the c.m.r. ratio.

After the source transformation we find the following model to be true,

with,

$$e_1 = \delta r_p i_{p_{co}} \tag{28}$$

$$e_2 = \delta\mu\, v_{g_{co}}. \tag{29}$$

We introduce two additional generators into the model, e_1 and e_2, to account for the unbalanced g_m and r_p.

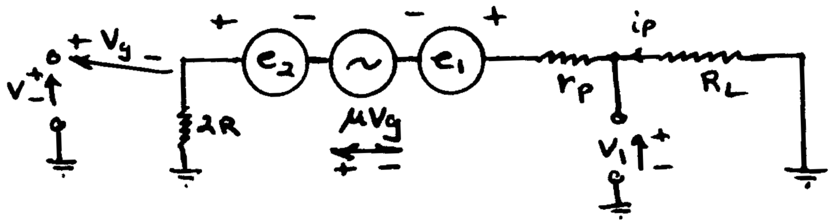


Figure Four: Unbalance Model

If we let,

$$\mu_a = \mu + \delta\mu \tag{30}$$

$$\mu_b = \mu - \delta\mu \tag{31}$$

and,

$$r_{pa} = r_p + \delta r_p \tag{32}$$

$$r_{pb} = r_p - \delta r_p \tag{33}$$

we find that,

$$i_p = \frac{\mu v_g + e_2 - e_1}{R_L + r_p + 2R} \tag{34}$$

We make an approximation by using the "original" values for i_p and V_g(28, 29), this is equivalent to ignoring higher order terms.

The derivation of the gain equations proceeds as derived earlier, except that we include e_1 and e_2.

$$v = v_g + i_p 2R \quad (35) \qquad\qquad V_1 = -i_p R_L \quad (36)$$

$$\text{C.M Result} \qquad V_{1c} = \frac{-R_L(\mu V_c + e_2 - e_1)}{R_L + r_p + (1+\mu)2R} \tag{37}$$

$$\text{D.M. Result} \qquad V_{1d} = -\frac{R_L(\mu V_d + e_2 - e_1)}{R_L + r_p} \tag{38}$$

Now $i_{p_{co}}$ is the common-mode plate current value with $e_1 = 0$ and $e_2 = 0$.

$$i_{p_{co}} = \frac{\mu V_c}{r_p + R_L + (1+\mu)2R} \tag{39}$$

Similarly,

$$V_{g_{co}} = V_c - 2R \cdot i_{p_{co}} \tag{40}$$

$$V_{g_{co}} = V_c - \frac{\mu 2R V_c}{r_p + R_L + 2R(1+\mu)} \tag{41}$$

$$\text{Thus,} \qquad V_{g_{co}} = V_c \left[\frac{r_p + R_L + 2R}{r_p + R_L + 2R(1+\mu)}\right] \tag{42}$$

Now, solving for the differential output voltage V_{1d} we observe the effects of unbalance. A differential output voltage results from a common-mode input voltage!

$$V_{1d} = -\frac{R_L}{R_L + r_p}\left[\mu V_d + \delta\mu V_c \frac{r_p + R_L + 2R}{r_p + R_L + 2R(1+\mu)} - \delta r_p \mu V_c \frac{1}{r_p + R_L + 2R(1+\mu)}\right] \tag{43}$$

rearranging terms,

$$V_{1d} = \frac{-\mu R_L}{r_p + R_L}\left[V_d + \frac{r_p + R_L + 2R}{r_p + R_L + 2R(1+\mu)}\left(\frac{\delta\mu}{\mu} - \frac{\delta r_p}{r_p}\cdot\frac{r_p}{r_p + R_L + 2R}\right)V_c\right] \quad (44)$$

In general we should write,

$$V_1(dm) = -A_{dc}\cdot V_c - A_{dd}\cdot V_d \quad (45)$$

$$V_1(cm) = -A_{cc}\cdot V_c - A_{cd}\cdot V_d \quad (46)$$

where two types of "cross terms" are evident. The common-mode rejection ratio is then,

$$H_c = \frac{A_{dd}}{A_{dc}} \quad (47)$$

or,

$$\frac{1}{H_c} = \frac{r_p + R_L + 2R}{r_p + R_L + 2R(1+\mu)}\left[\frac{\delta\mu}{\mu} - \frac{\delta r_p}{r_p}\cdot\frac{r_p}{r_p + R_L + 2R}\right] \quad (48)$$

If we let $R \longrightarrow \infty$, we find that,

$$H_c\Big|_{R\to\infty} = \frac{\mu(1+\mu)}{\delta\mu} \quad (49)$$

or,

$$CMR = 20 \log_{10} \frac{\mu(1+\mu)}{\delta\mu} \qquad (50)$$

If we then return to the controlled voltage source model we again use,

$$\mu = g_m r_p \qquad (51)$$

Thus,

$$\frac{1}{H_c} = \frac{r_p + R_L + 2R}{r_p + R_L + 2R(1+g_m r_p)} \left[\frac{\delta g_m}{g_m} + \frac{\delta r_p}{r_p} \left(1 - \frac{r_p}{r_p + R_L + 2R} \right) \right] \qquad (52)$$

If we ignore a term in $\delta g_m \cdot \delta r_p$, we may use,

$$\frac{\delta\mu}{\mu} = \frac{\delta g_m}{g_m} + \frac{\delta r_p}{r_p} \qquad (53)$$

Thus for $R \to \infty$,

$$\frac{1}{H_c} = \frac{1}{1+g_m r_p} \left(\frac{\delta g_m}{g_m} + \frac{\delta r_p}{r_p} \right) \qquad (54)$$

or,

$$H_c\Big|_{R\to\infty} = \frac{1+g_m r_p}{\left(\frac{\delta g_m}{g_m} + \frac{\delta r_p}{r_p}\right)} \qquad (55)$$

Example:

If we use values of r_p and g_m for the Amelco, Inc. DA-402 F.E.T., we find that,

$$g_m = 3500 \times 10^{-6}\,\text{mhos} \qquad r_p(@\,1\,\text{mc}) = \frac{1}{20\times 10^{-6}}\,\text{ohms} = 50\text{K}$$

$$\delta g_m = \pm 2.5\% \qquad \delta r_p = \pm 2.5\% \quad (\text{choose})$$

$$H_c = \frac{1 + 50\times 10^{3} \times 3500 \times 10^{-6}}{\frac{1.25\times 10^{3}}{50\times 10^{3}} + \frac{8.75\times 10^{-5}}{3.5\times 10^{-3}}} = 3500.$$

Thus, the maximum possible value for the common-mode rejection is:

$$\begin{aligned} CMR &= 20 \log_{10} 3500 \\ &= 71.\,\text{db} \qquad (\text{with} \pm 2.5\%\ r_p \text{ and } g_m). \end{aligned}$$

check: using $\frac{\mu(1+\mu)}{\delta\mu}$ we get $\frac{175(1+175)}{175(.05)} = 3500$ ✓

or,

$$H_c\Big|_{R\to\infty} = \frac{1+g_m r_p}{\left(\frac{\delta g_m}{g_m} + \frac{\delta r_p}{r_p}\right)} \qquad (55)$$

Example:

If we use values of r_p and g_m for the Amelco, Inc. DA-402 F.E.T., we find that,

$$g_m = 3500 \times 10^{-6} \text{ mhos} \qquad r_p(@\ 1\text{mc}) = \frac{1}{20 \times 10^{-6}} \text{ ohms} = 50K$$

$$\delta g_m = \pm 2.5\% \qquad \delta r_p = \pm 2.5\% \quad (\text{choose})$$

$$H_c = \frac{1 + 50 \times 10^3 \times 3500 \times 10^{-6}}{\frac{1.25 \times 10^3}{50 \times 10^3} + \frac{8.75 \times 10^{-5}}{3.5 \times 10^{-3}}} = 3500.$$

Thus, the maximum possible value for the common-mode rejection is:

$$CMR = 20 \log_{10} 3500$$
$$= 71.\text{ db} \qquad (\text{with} \pm 2.5\%\ r_p \text{ and } g_m).$$

check: using $\frac{\mu(1+\mu)}{\delta\mu}$ we get $\frac{175(1+175)}{175(.05)} = 3500$ ✓

APPENDIX IV

II. Recovery Time Analysis

We define the recovery time, for the amplifier shown in Figure 10, to be the time in which the differential amplifier output signal returns to ±10. millivolts of the normal 10. mv output offset. The recovery time shall be measured by introducing a differential input signal of one volt for 100. milliseconds. Our design goal for the EEG amplifier shall be a recovery time of 6.0 seconds.

Since the gain of the first stage is on the order of 3.0, we use small signal analysis. The second stage, however, has a gain of fifty, and in response to a one volt input pulse, will be cut off or saturated. In the second stage we must, therefore, use large signal techniques.

Figure 5 shows our model for the EEG amplifier. All voltages noted are differential.

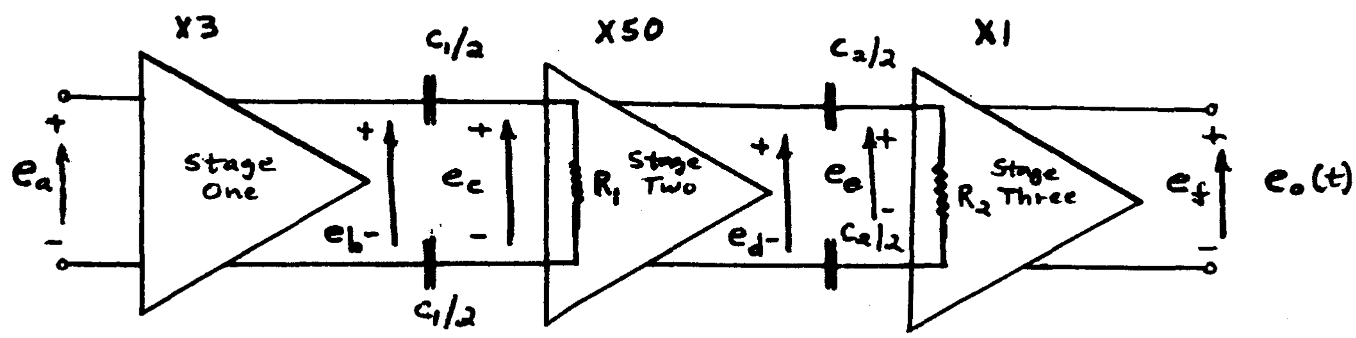


Figure Five: Amplifier Circuit Model

Figure 6 shows circuit waveforms for the first and second stages. Since the first stage operates in a small signal mode, the output is simply the gain times the input. C_1 and R_1 are the effective circuit values. The value for R_1 includes the input resistance of stage two and the output resistance of stage one. The waveform, e_c, is primarily determined by the relationship of $\tau_1 = R_1C_1$ to the input pulse width. We may compute E_x from,

$$E_x = Ae^{-t/\tau_1}$$

where,

$$t = .1 \text{ sec. and } A = 3.0 \text{ volts}$$

Now, τ must be,

$$\tau = \frac{1}{2\pi f} = R_1\ C_1$$

and for f = .2 cps,

$$\tau = .8 \text{ sec.}$$

Thus,

$$E_x = 3.0\ e^{-.1/.8} = 2.65 \text{ volts}$$

and,

$$\delta e = 3.0 - 2.65 = .35 \text{ volts}$$

Due to the high gain of stage two, large signal analysis is required. The two sides of the stage are driven, respectively, into cutoff and saturation for any input signal greater than or equal to ±.2 volts. The output dynamic range of stage two is ±10.0 volts. For the positive going portion of e_c, e_d will remain cuttoff at +10. volts. For the negative going portion of e_c, e_d will remain at -10.0 volts until e_c is less than -.2 volts. This occurs at time t_1. To find t_1,

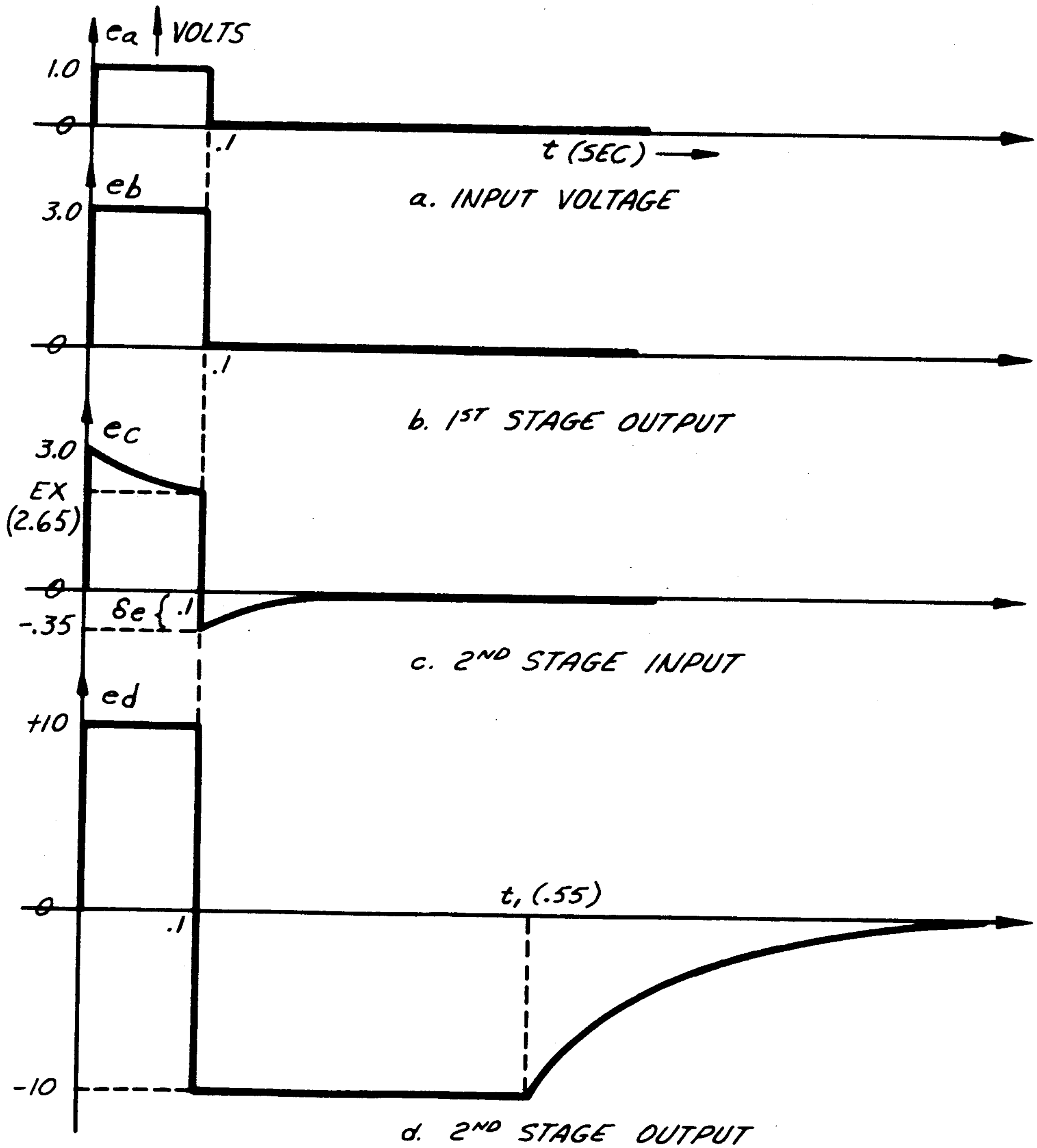


FIGURE SIX CIRCUIT WAVETURNS

$$e_c = \Sigma e \cdot e^{-t/.8} \qquad t > .1$$

When $t = t_1$, $e_c = .2$ volts.

Thus, $$.2 = .35e^{-t_1/.8}$$

or, $$t_1 = .8 \,(\ln 1.75)$$

$$t_1 = .45 \text{ sec.}$$

Referring to Figure 7, the level, E_y, may be computed as we previously computed E_x.

$$Ey = 10\ e^{-.1/.8} = 8.8 \text{ volts}$$

Thus,

$$\Sigma e_e = 1.20 \text{ volts.}$$

The level, E_z , may be computed:

$$E_z = 11.2\ e^{-.45/.8}$$

assuming that $R_1C_1 = R_2C_2 = .8$ sec.

So,

$$E_z = 6.4 \text{ volts.}$$

By the linear property of the passive bilateral coupling circuit R_2C_2, we can now disassemble e_d into its component waveforms, Figure 8, and compute e_e as the sum of the component responses.

The component responses are all obvious except the response to component IV.

Responses: I: $+10\ e^{-t/.8}$

II : $-20\ e^{-(t-.1)/.8}$

III: $+10\ e^{-(t-.55)/.8}$

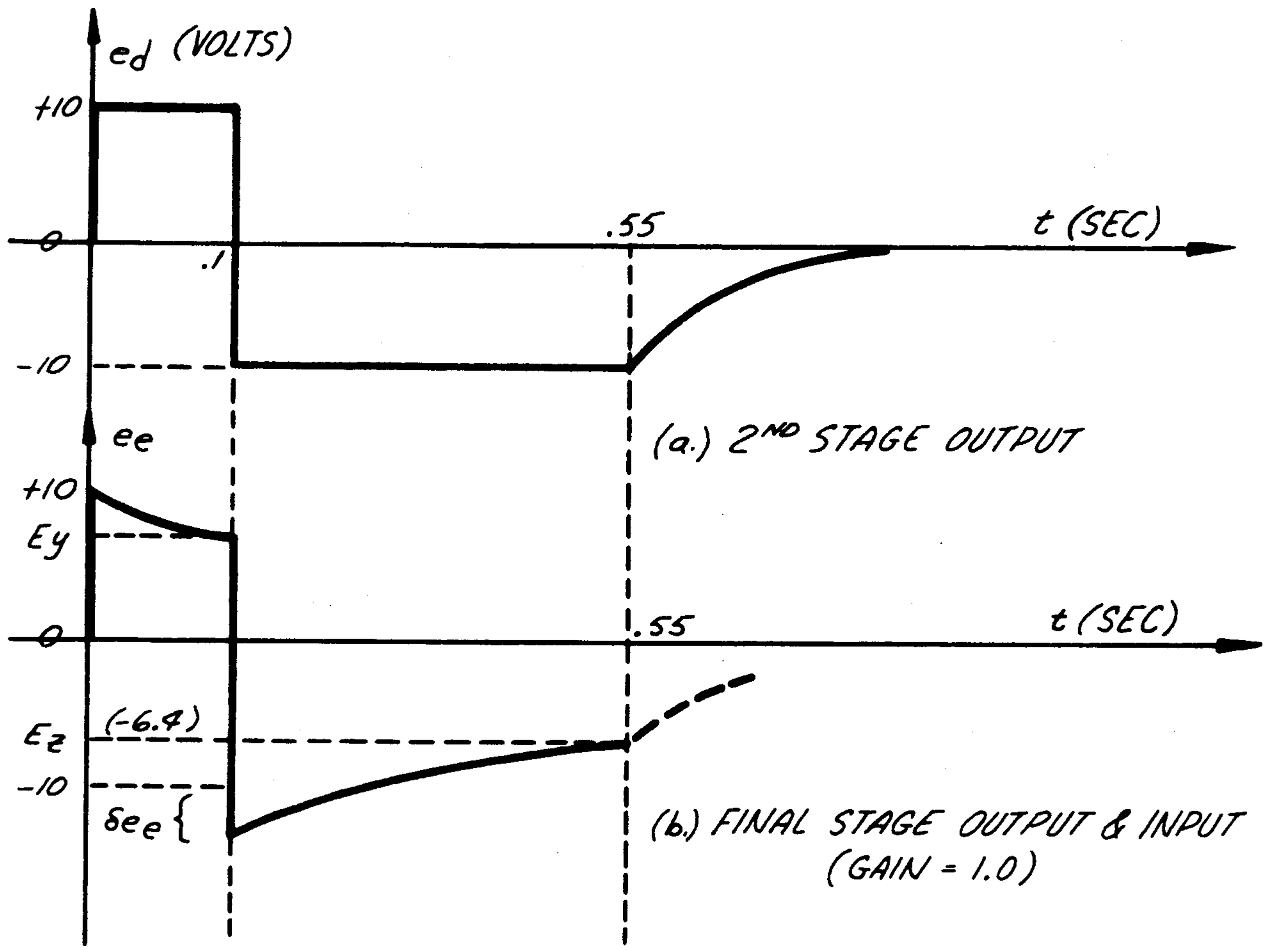


FIGURE SEVEN OUTPUT STAGE WAVEFORMS

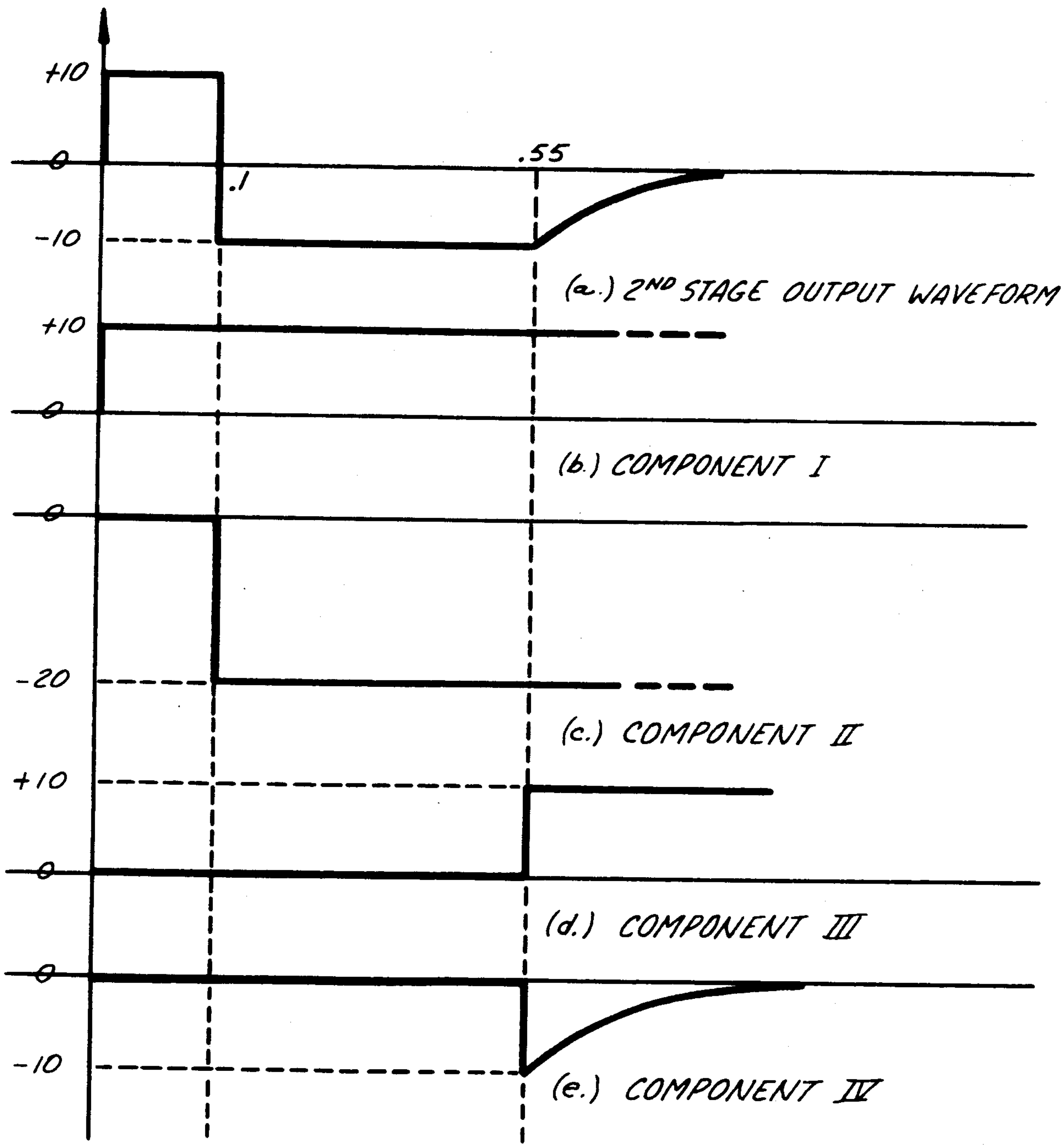


FIGURE EIGHT COMPONENTS OF ee

To compute the response to component IV we use LaPlace Transforms. The problem is simply that of the response of a series RC circuit to an exponential drive. We still assume $R_1C_1 = R_2C_2 = .8$ sec. The transfer function for the R_2C_2 network is,

$$H(s) = \frac{R_2C_2S}{R_2C_2S+1}$$

The input signal is

$$e_1(t) = -10\ e^{-(t^1)/.8} \qquad t^1 = t - .55$$

with transform,

$$E_1(s) = \frac{-10}{s + 1/.8}$$

Thus,

$$E_o(s) = \frac{-10s}{(s + 1/.8)(s + 1/.8)}$$

and

$$e_o(t) = -10(1 - 1/.8\ t^1)\ e^{-t^1/.8}$$

or

$$e_o(t) = -10\ e^{-(t - .55)/.8} + 12.5\ t\ e^{-(t - .55)/.8}$$

Thus,

$$e_o(t) = 10\ e^{-t/.8} - 20\ e^{-(t - .1)/.8} + 10\ e^{-(t - .55)/.8}$$

$$-10\ e^{-(t - .55)/.8} + 12.5t\ e^{-(t - .55)/.8}$$

from which we may cancel two terms.

The term involving $te^{-t/\tau}$ peaks at about $t = 1.35$. The shape of the transient response beyond $t = 1.0$ is strongly influenced by this term. A plot of the final output waveform follows in Figure 9. Since the last stage is a d.c. coupled emitter follower, $e_f = e_e$.

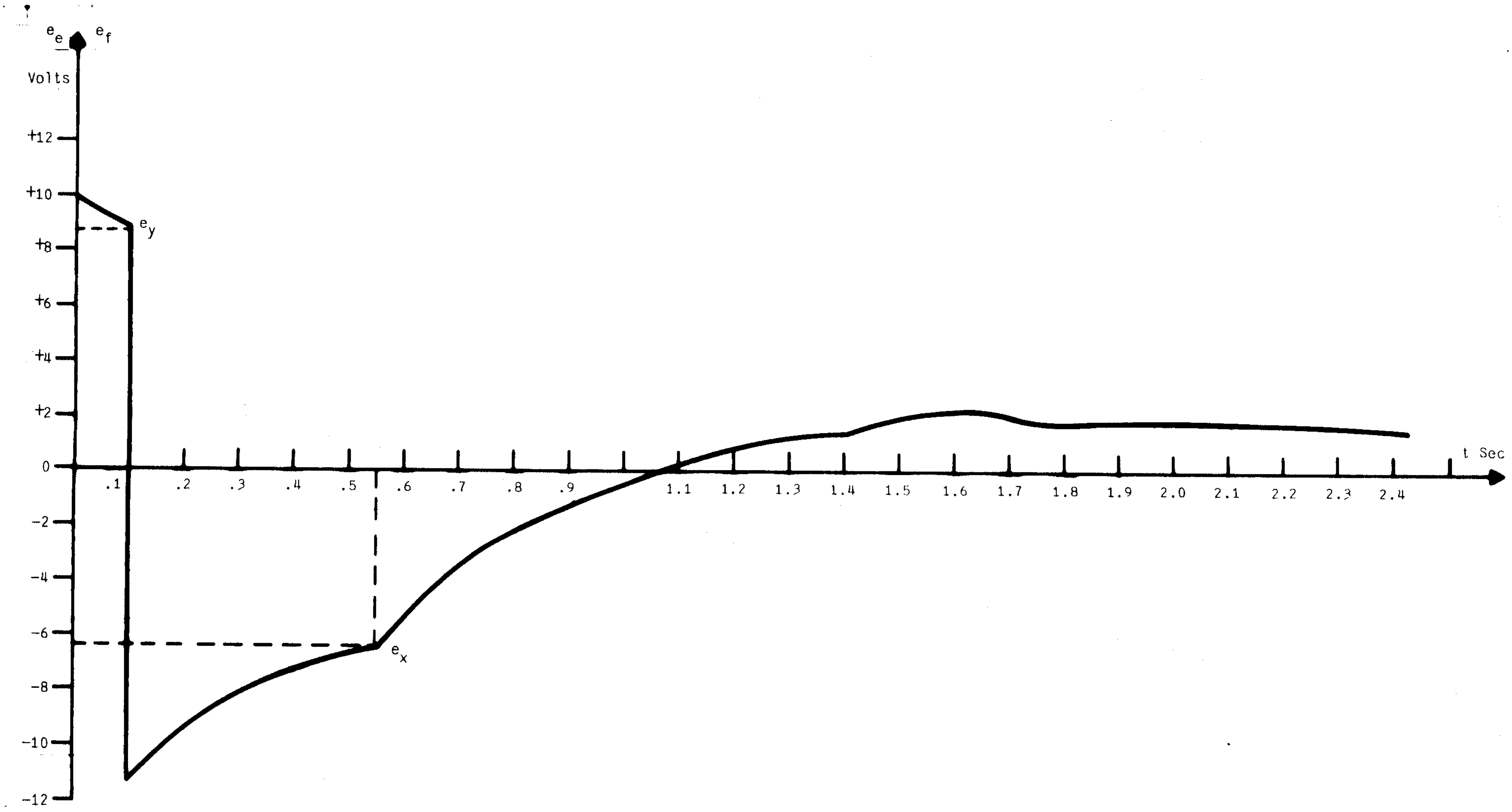
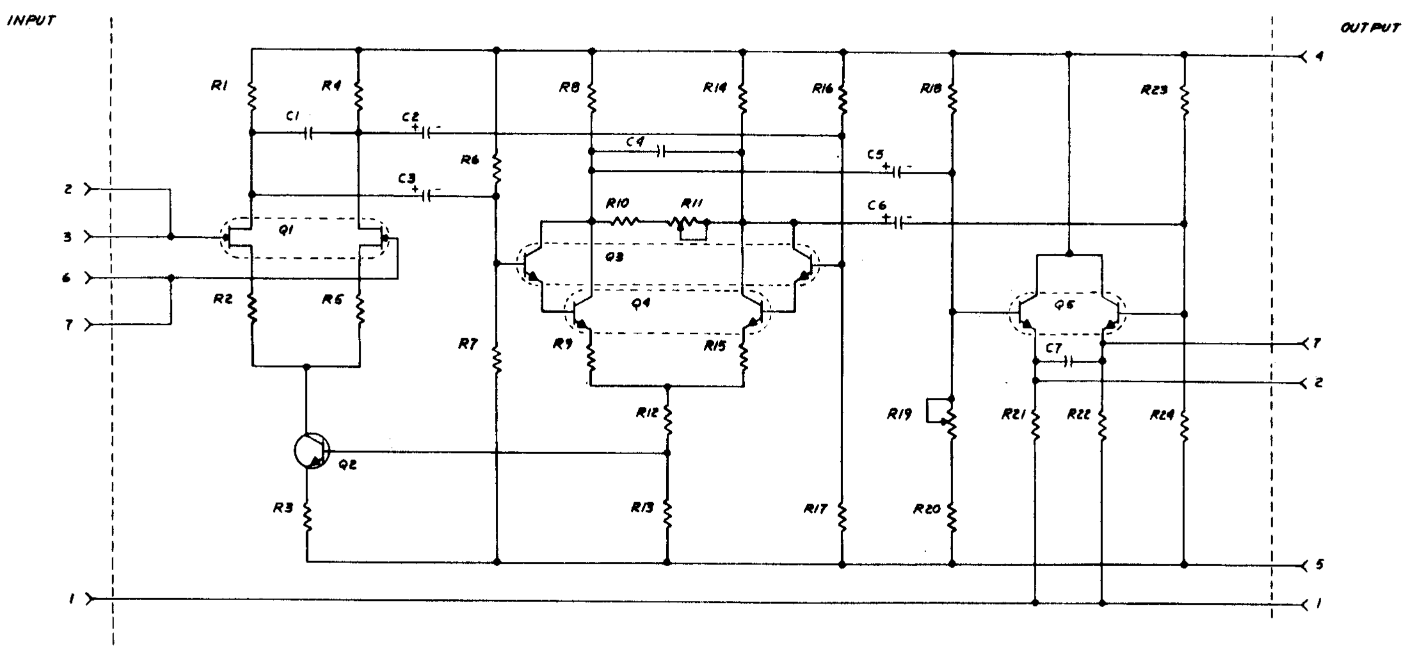


Figure 9. Output Stage Waveform



REF - RECEPTACLE PIN ASSIGNMENTS			
PIN	INPUT	PIN	OUTPUT
1.	SIGNAL COMMON	1.	POWER COMMON
2.	INPUT A	2.	OUTPUT A
3.	INPUT A	3.	NO CONNECTION
4.	NO CONNECTION	4.	+10 VOLTS DC
5.	NO CONNECTION	5.	-10 VOLTS DC
6.	INPUT B	6.	CALIBRATION (OR N.C.)
7.	INPUT B	7.	OUTPUT B

4. ALL REF DESIGNATIONS ARE ABBREVIATED AND SHALL BE PRECEDED BY SUB-ASSY OR ASSY NUMBERS OR BOTH.
3. ALL RESISTOR VALUES ARE IN OHMS ± 1 %, 1/8 W.
2. INTERPRET REF DESIGNATIONS PER MIL-STD 16.
1. INTERPRET SYMBOLS PER MIL-STD 15
NOTES: UNLESS OTHERWISE SPECIFIED

SYM	ZONE	REVISIONS DESCRIPTION	DATE	APPROVED

QTY REQD	BECKMAN NO.	ITEM NO.	NOMENCLATURE OR DESCRIPTION	PART OR IDENTIFYING NO.	CODE IDENT	MATERIAL	SPEC. NOTES, SIZES, VENDORS

LIST OF MATERIALS OR PARTS LIST

NEXT ASSY	USED ON
APPLICATION	

MATERIAL

FINISH

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES
X ± .050 ANGULAR ± 0° 30'
XX ± .020
XXX ± .005 MACH. SURF. ✓
THREADS: CLASS 2A OR 2B
REMOVE BURRS & SHARP EDGES .020 MAX.
MACH. SURF. FLAT WITHIN .001 IN/IN
OTHER SURF. FLAT WITHIN .005 IN/IN
DO NOT SCALE DRAWING

	BY	DATE
DR	L LEBLANC	9-11-69
CHK	J. K.L.Pfe	9-11-69
ENGR	[illegible]	9-11-69
APPD	C Kaiser	9-11-69
APPD	A. Pacale	9/11/69

Beckman® INSTRUMENTS, INC. 2500 HARBOR BLVD. FULLERTON, CALIF.

TITLE PRELIMINARY
EEG SIGNAL CONDITIONER
SCHEMATIC DIAGRAM

CODE IDENT NO.	SIZE	
05721	D	020-141851

SCALE NONE — SHEET 1 OF 1

020-141851

Figure 10

APPENDIX V.

Appendix V. Recovery Time - Frequency Response Relationship

A. A Simple Case

To determine the interrelationship between frequency response and recovery time, we will first consider the simple, highpass filter, or coupling network shown in Figure 1.

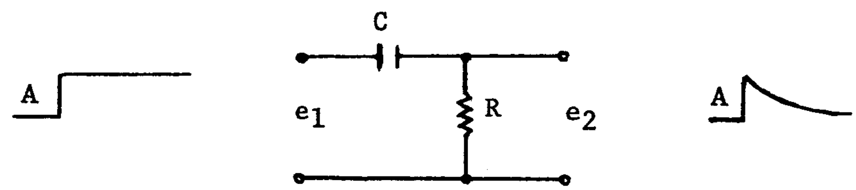


Figure 1. Simple Coupling Network

The filter 3 db down frequency, f_1, is given by,

$$\omega RC = 1 \qquad (1)$$

where $$\omega = 2\pi f_1 \qquad (2)$$

or $$f_1 = \frac{1}{2\pi RC} \qquad (3)$$

We define the recovery time, t_1, for such a network, to be the time required for the output to settle to within an arbitrary voltage difference (e.g. ± 10. mv) from its quiescent output level (zero), after an input pulse (e.g., 1 volt for 100 m.s.). The simple transient shown in Figure 1 is given by,

$$e_2 = Ae^{-t/\tau}, \ \tau = RC \qquad (4)$$

The recovery time, t_1, is then, for $e_2 = 10.$ mv,

$$t_1 = -RC \quad . \quad \left[\ln(10^{-2}). - \ln A\right] \qquad (5)$$

or, $$t_1 = +RC \quad . \quad \left[4.61 + \ln A\right] \qquad (6)$$

For this simple circuit, with A = 1, the recovery time and low frequency 3 db point are related by,

$$t_1 = \frac{4.61}{2\pi f_1} = .74\left(\frac{1}{f_1}\right) \qquad (7)$$

Although this circuit is exceedingly simple, it serves to illustrate the strong relationship between recovery time and frequency response. The equation (7) is plotted in Figure 2. The relationship shown in Figure 2 is obviously hyperbolic. It is interesting to note that only the points on the locus are possible sets of values.

B. The EEG Amplifier

In the simple example above, the desired specifications are met. There are four important differences between the full EEG amplifier design and the simple RC circuit that makes this impossible, however:

1. The amplifier has a gain, 100-150,
2. The amplifier has dynamic range limits at the supply voltages, ±10. volts, and
3. The amplifier must have two RC coupling networks.

Differences 1 and 2 are self-evident. Let us, at this point, justify (3). Since the amplifier must operate with a differential d.c. input signal of one volt, it is obvious that the first stage can have a gain no greater than 3. and must be a.c. coupled to the second stage. If this coupling network were omitted, the required gain of 100-150 would cause the amplifier to be driven into cutoff or saturation at the gain stage. A second RC coupling network is also necessary to meet the difficult ±200. μv. output-offset-temperature specification. This requirement is equivalent to about 5 μv./°C and can be met by a single emitter follower, output stage. The output stage must be RC coupled to the gain stage to avoid the temperature drift of the gain stage. This situation could not be improved by the use of a high gain stage with feedback as the temperature drift would still be an equivalent input drift multiplied by the amplifier gain.

In Appendix II of Progress Report I, we found an expression for the amplifier output transient,

$$e_o(t) = 10\, e^{-t/\tau} - 20\, e^{-(t-.1)/\tau} + 12.5\, te^{-(t-.55)/\tau} \quad (8)$$

If we take the logarithm of both sides of equation 8 to solve for t_1, (at $t = t_1$, $e_o = 10^{-2}$),

$$t_1 - C_2 \ln t_1 = -C_1, \quad (9)$$

we discover that the equation is transcendental. It would not be correct to expand the logarithm in a series unless a large number of terms were used. We, thus, cannot obtain a closed form analytical solution to the relationship between recovery time and frequency response for the full circuit. We can of course obtain experimental results, and these are shown in Figure 3.

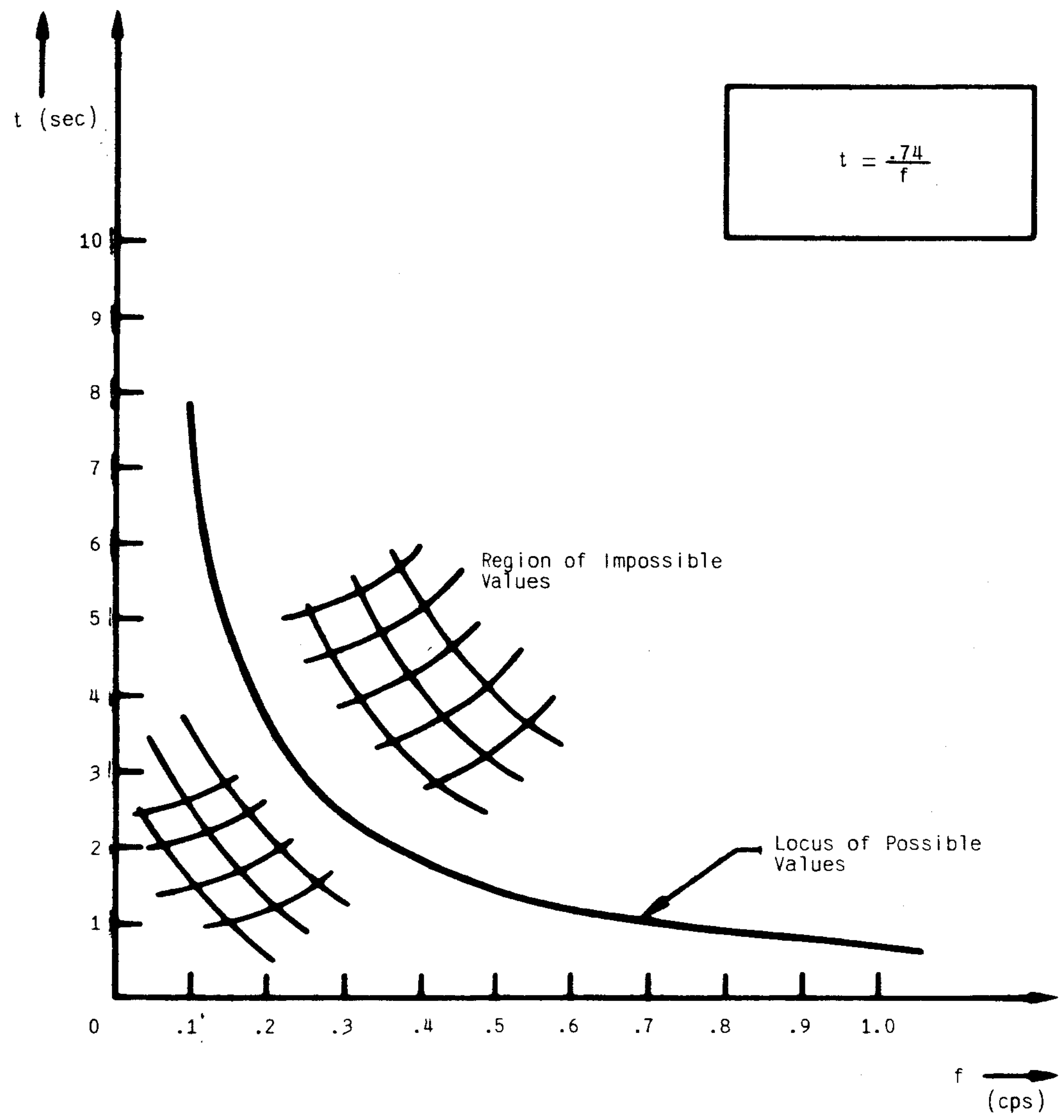


Figure 2. Recovery Time vs. Frequency Response for Simple RC Circuit

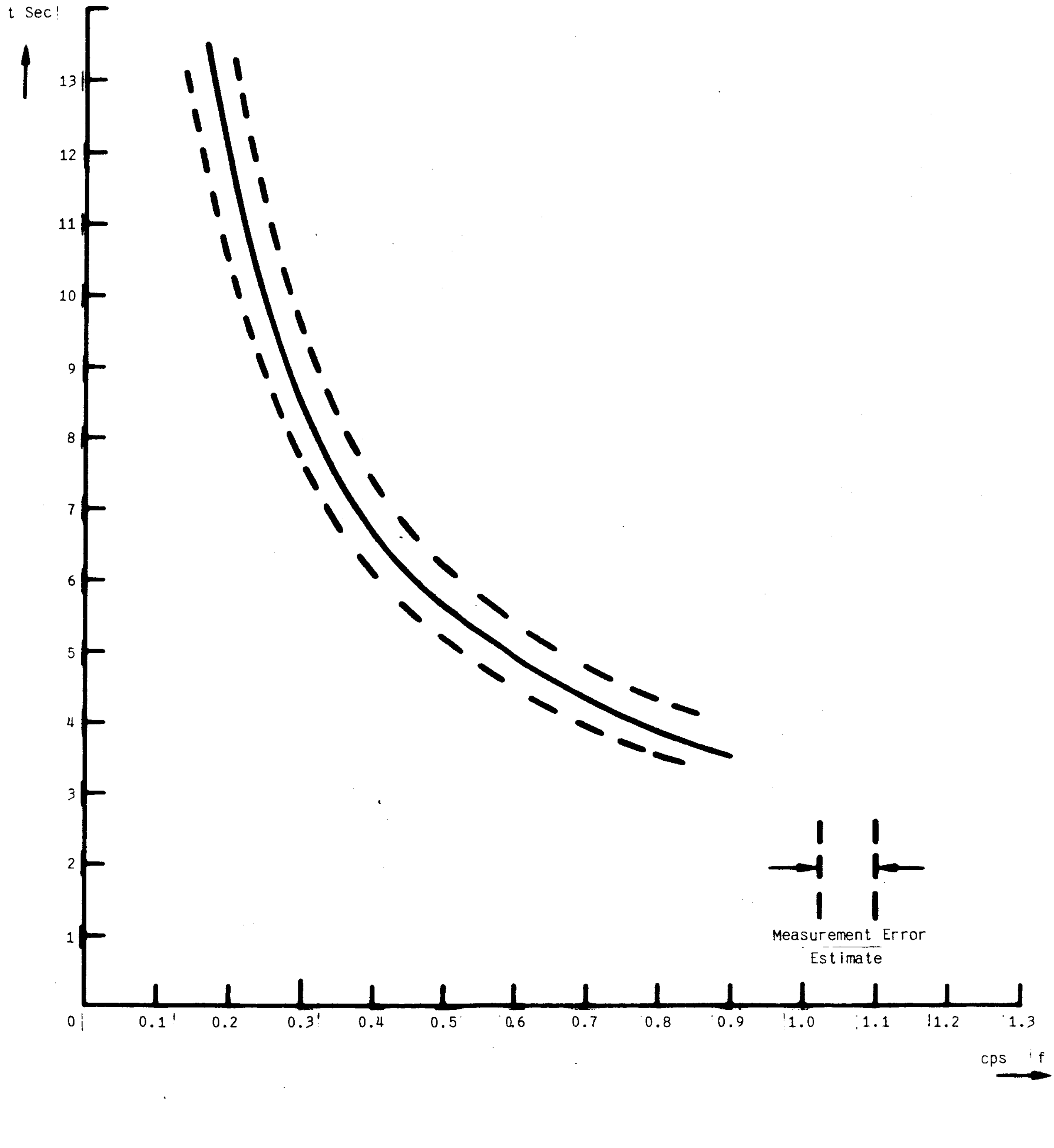


Figure 3. EEG Recovery Time vs. Frequency Response